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GEOLOGICAL SURVEY

Characteristics of Mineral Deposit Occurrences

Compiled by
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This report is preliminary and has not been edited or reviewed
for conformity with U.S. Geological Survey
editorial standards and stratigraphic nomenclature.

CONTENTS

	Page
Foreward, by R. L. Erickson.....	iii
Characteristics of metallic deposits associated with ultramafic and mafic rocks, by Norman J. Page, Michael P. Foose, and Bruce R. Lipin.....	1
Magmatic nickel sulfides, by M. P. Foose.....	13
Stratiform chromite, by Bruce Lipin and Norman Page.....	18
Kimberlites of Conterminous United States, by A. V. Heyl.....	21
A generalized empirical model for porphyry copper deposits, by D. P. Cox;.....	27
with a section on Geochemical expression by M. A. Chaffee,.....	33
and a section on Geophysical expressions of porphyry copper deposits, southwest United States, by C. K. Moss.....	35
Preliminary model outline for fluorine-deficient porphyry molybdenum deposits, by T. G. Theodore.....	37
Granite molybdenite systems, by S. D. Ludington.....	43
Characteristics of the Colorado-type (Climax-type) molybdenum deposits readily recognized at the surface, by P. K. Theobald, Jr.....	47
Model for contact metasomatic tungsten/copper/gold deposits, by J. E. Elliott.....	49
Tin greisen model, by B. L. Reed.....	55
Diagnostic features of fluoride-related beryllium deposits, by W. R. Griffitts.....	62
Spor Mountain Be-F-U deposits, by D. A. Lindsey and D. R. Shawe.....	67
Orogenic (metamorphic-hosted) gold-quartz veins, by J. K. Bohlke.....	70
Volcanic exhalative massive sulfide deposits, by B. R. Doe.....	77
Cyprus-type volcanogenic massive sulfide deposits in ophiolites, by R. A. Koski.....	82
Assessment of the potential for volcanogenic massive sulfide deposits in differentiated volcanic rocks--a field guide, by R. L. Earhart.....	87
Stratabound Precambrian sulfide deposits, Colorado and southern Wyoming, by D. M. Sheridan and W. H. Raymond.....	92
Zinc-rich massive sulfide deposits, northern Cordillera: some preliminary exploration guides from the western Brooks Range, Alaska, by P. K. Theobald, Jr.....	100
Belt stratabound Cu-Ag, by J. E. Harrison.....	102
Sullivan-type stratabound Pb-Zn-Ag, by J. E. Harrison.....	105
Stratabound massive sulfide--deposits in an island-arc belt of volcanic/volcaniclastic rocks, by Leslie Cox.....	107
Blue Ridge massive sulfides, by J. E. Gair.....	112
The geological attributes of Au-Ag-base metal epithermal deposits, by B. R. Berger.....	119
Silver/base metal epithermal deposits, by Paul Barton.....	127
Hot-spring type, large tonnage, low-grade gold deposits, by M. L. Silberman.....	131
Occurrence model for enargite-gold deposits, by R. P. Ashley.....	144
Model for hydrothermal alunite deposits, R. B. Hall.....	148
A prospecting model for stratabound lead-zinc(-barite-fluorite) deposits ("Mississippi Valley-type" deposits), by W. P. Pratt.....	155

	Page
Mineral deposit occurrence model for the Viburnum Trend subregion of the Southeast Missouri base metal and barite district, by A. V. Heyl.....	158
Stratabound Zn-Pb in marbles of Grenville Complex, Balmat-Edwards, New York, by C. E. Brown.....	172
Model of Central Pennsylvania lead-zinc mineralization, by S. S. Howe.....	175
Summary of the general geologic characteristics of sandstone- hosted lead-zinc deposits, J. A. Briskey.....	183
Black shales as sources of minerals and fuels, by J. S. Leventhal, J. R. Hatch, M. A. Arthur, and H. A. Tourtelot.....	186
Metalliferous organic-rich paleozoic marine strata of the Western United States, by G. A. Desborough and F. G. Poole.....	193
Copper shales, by D. A. Lindsey.....	196
Preliminary concepts of a simple existence model for large sandstone uranium deposits, by W. I. Finch.....	200
Empirical recognition criteria for unconformity-type uranium deposits applied to some Proterozoic terranes in the United States, by J. T. Nash.....	205
Badlands-type molybdenum-uranium deposits in sandstone, by W. H. Raymond.....	218
Occurrence model for sedimentary manganese deposits, by William Cannon and Eric Force.....	222
Laterite-type bauxite--Al-Ga, by S. H. Patterson.....	223
Lithium-rich clays, by Sigrid Asher-Bolinder.....	225
Bedded barite, by K. B. Ketner.....	230
Bedded barite, by F. G. Poole, D. R. Shawe, R. O. Rye, and G. A. Desborough.....	232
Great Basin phosphate, by K. B. Ketner.....	235
High-grade silica deposits, by K. B. Ketner.....	237
New York talc, by C. E. Brown.....	239
Model for zeolites in saline, alkaline-lake deposits, by R. A. Sheppard.....	241
Depositional model for bedded sodium carbonate deposits, by John R. Dyni.....	244

FOREWORD

A primary responsibility of the Geological Survey is to assess the mineral potential of the nation, particularly of the public lands. In order to carry out this formidable task, we must improve and sharpen our resource assessment technology and methodology, particularly in our ability to predict the occurrence of unexposed mineral deposits. We are now performing resource appraisal studies in which we require that our scientists evaluate the possibilities for a large variety of possible types in a large variety of geologic terranes. As Paul Barton has said, "It is analogous to expecting every representative to the UN to be able to speak English, French, German, Navajo, Basque, Arabian, Chinese . . ."

Given these facts, it is clear that the Division must provide, as quickly as possible, the opportunity for our scientists to learn the different "languages" of different mineral deposit types. One of the ways to help us learn the "languages" is to develop mineral occurrence models that emphasize the geologic, geochemical, and geophysical environments and characteristics of different types of mineral deposits--and to compile the models into an easily modified and continually expanding working guidebook for project-level geoscientists.

In order to "make a beginning," open meetings with "Friends of Mineral Deposits"--Geologic Division were held at Reston, Denver, and Menlo Park in April 1981 to discuss the need and purpose of the modelling program and to solicit "models" from scientists in the Division who have expert insight and knowledge of the characteristics of specific types of ore deposits. The compendium of papers that follows is the initial response to that solicitation. Authors were asked not to be concerned about production of a scholarly treatise or literary excellence but to focus on criteria for recognition of favorable geologic terranes and "ore guides" or "clues to ore" within that terrane--whether or not they can explain the geologic processes involved.

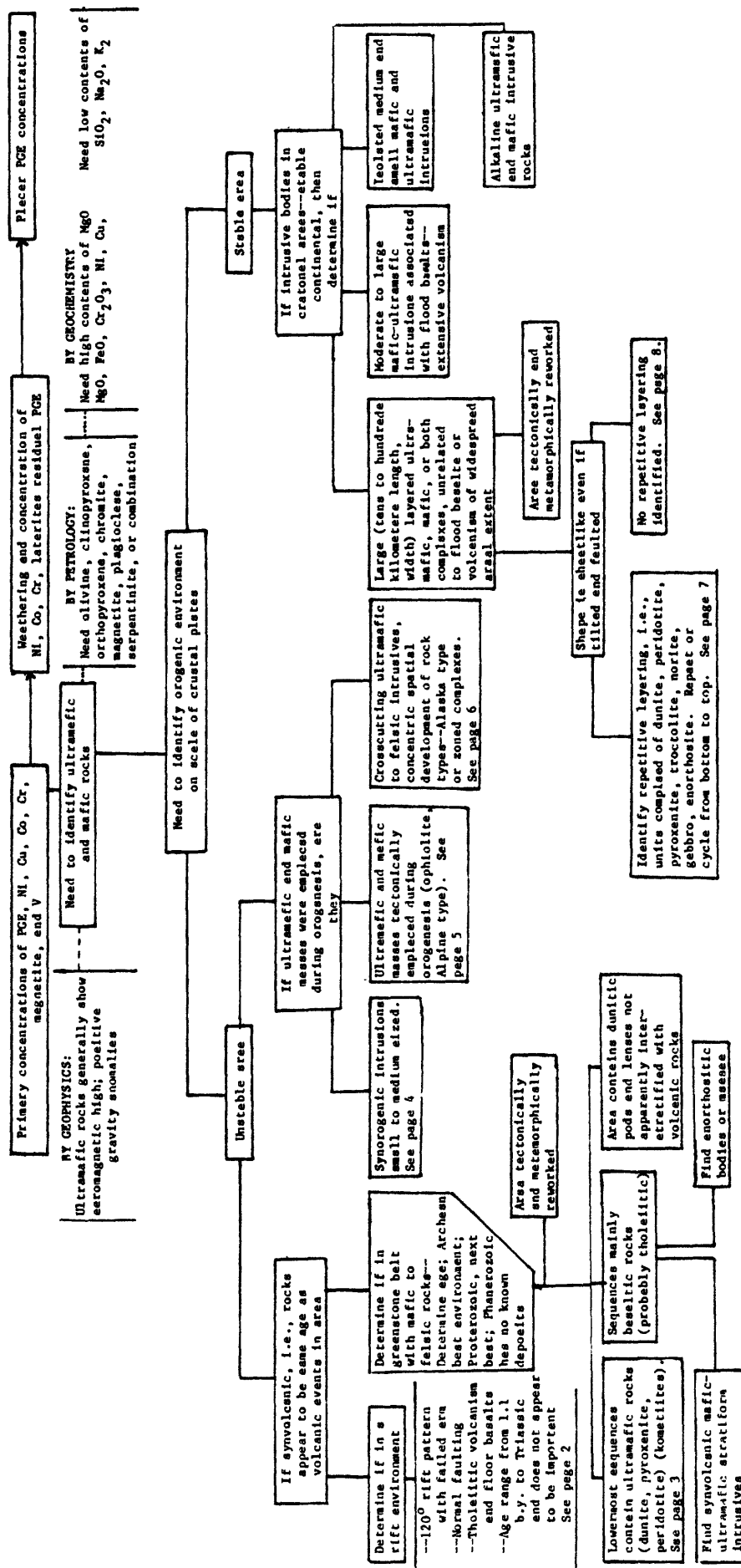
I have made no attempt to recast the "models" into a standard format believing that the informality and candor of individual papers is a valuable contribution itself and should be preserved--at least in this informal guidebook. A few of the papers are cast in the proto-prototype-checklist format suggested by Paul Barton. Most contributors stress that their "model" is a preliminary or experimental first draft; most anticipate modifications or changes and would welcome comment or contributions of additional or new information where possible. Many "models" are incomplete especially in the areas of geochemical and geophysical characteristics. Nevertheless, they contain a great deal of valuable and readily useable information distilled from many man-years of experience and insight.

The guidebook is intended to be dynamic--in the sense that we will change, add, or delete as contributions are received from other Division scientists, particularly those who have not yet fulfilled their commitment to help in this effort.

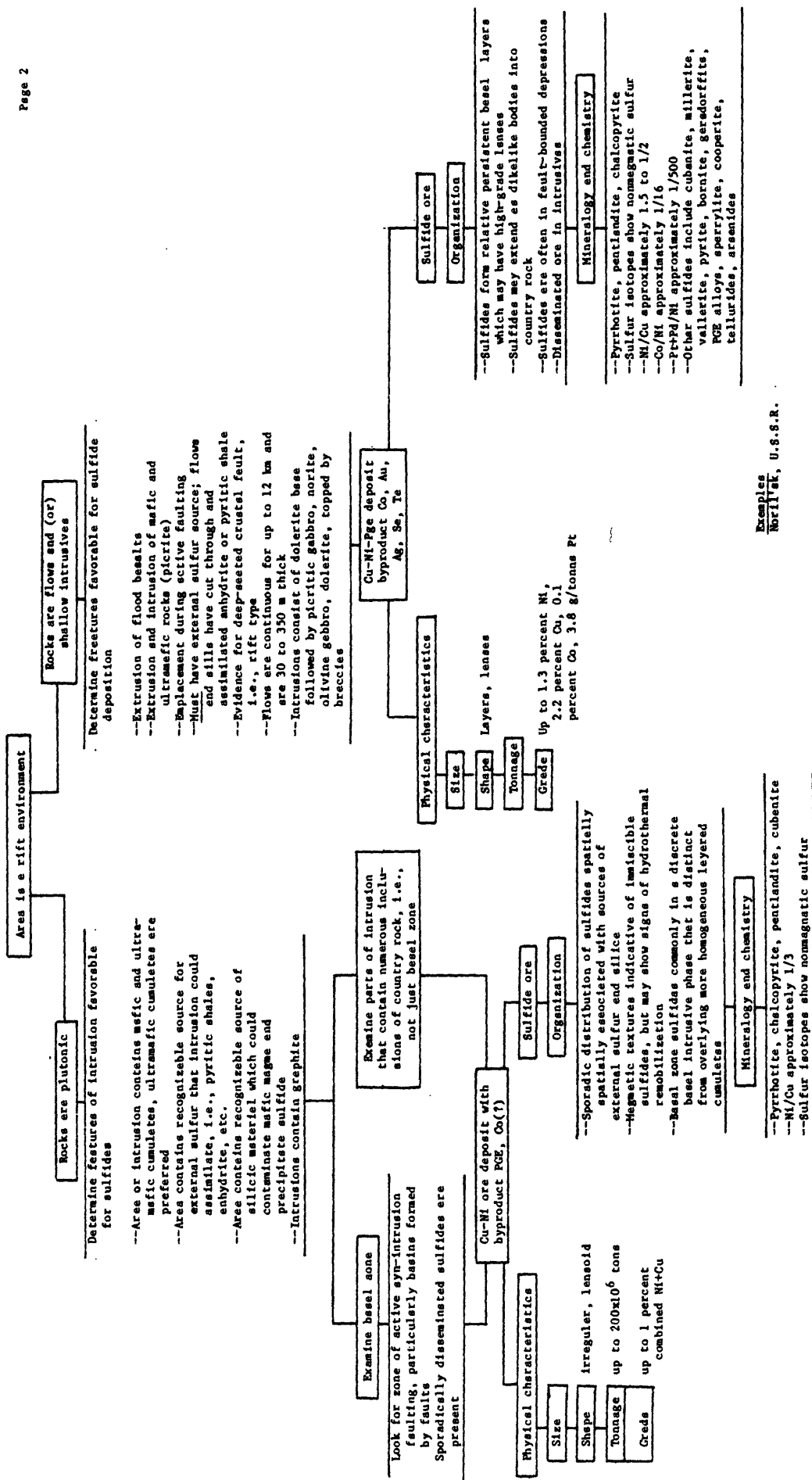
I feel confident that all who read this group of preliminary short papers will recognize the opportunity and potential that the Geologic Division has to develop, compile, and publish a really monumental work on the characteristics of different types of mineral deposits. This compilation is but a small sample of the staggering amount of critical information about mineral deposits that exists in the heads of our Division scientists. We must find a way to access, extract, and disseminate that hard-won knowledge to other Division scientists and to the world-wide earth science community.

Ralph L. Erickson

by Normaen J Page, Michael P. Foote, and Bruce R. Lipin



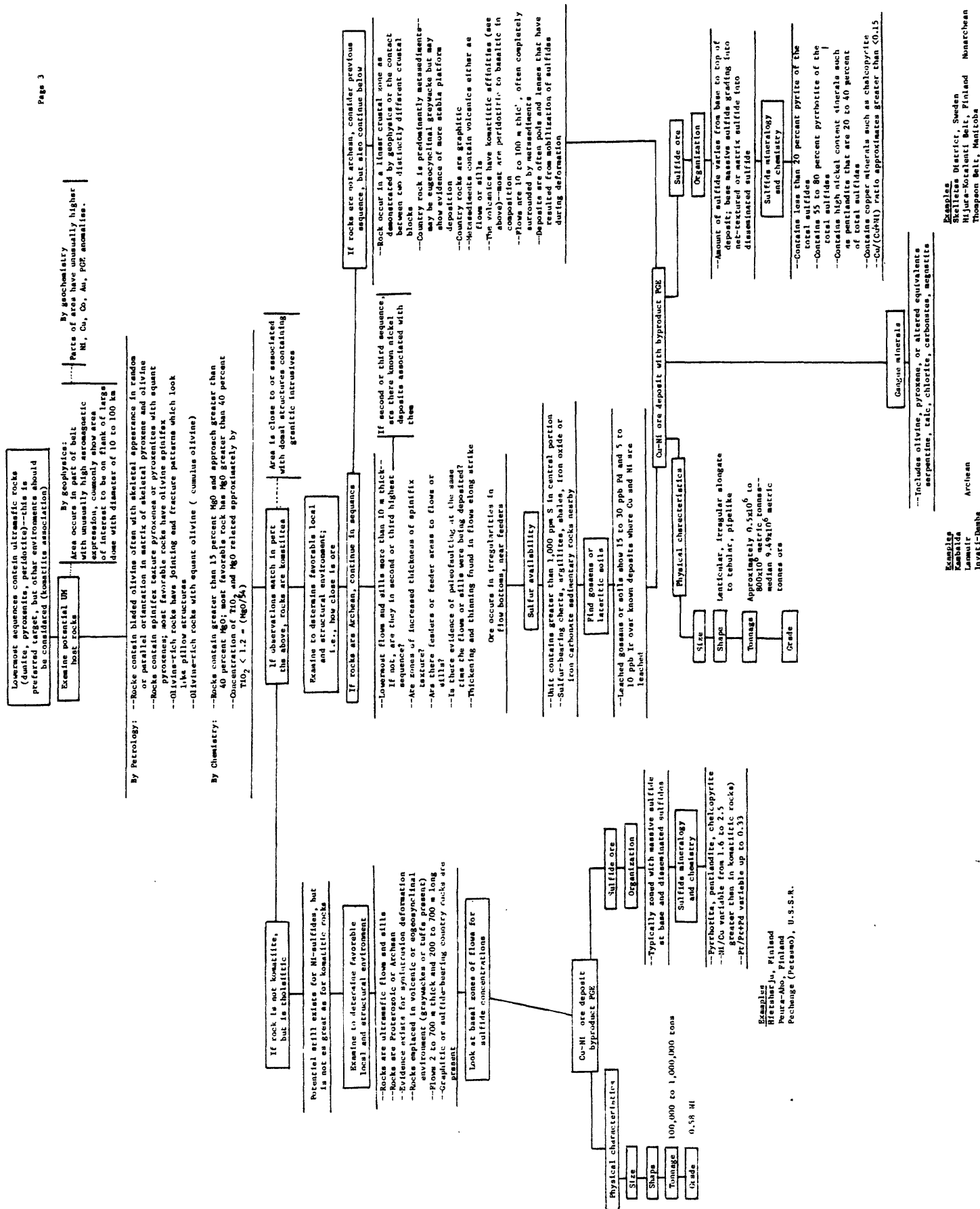
These models are in preliminary form; they contain no documentation and are not intended as genetic models.

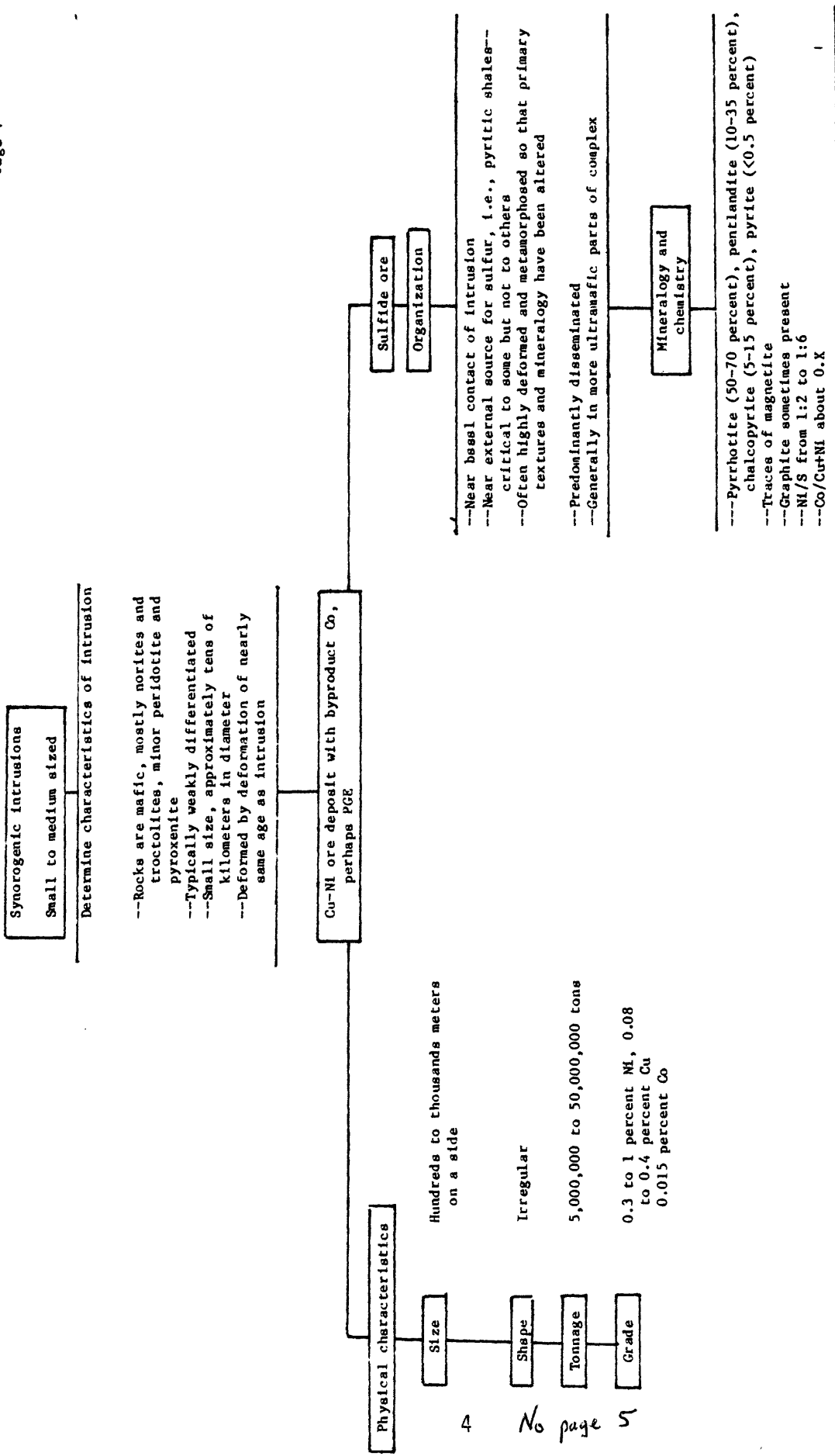


Examples
Noril'sk, U.S.S.R.

Example

Duluth Complex, Minnesota





Examples
Rana, Norway
Kvikkne, Norway
Moxie, Maine

Ultramafic and mafic masses tectonically emplaced during orogenesis (ophiolite; alpine)

- Area contains peridotite masses that have a tectonite fabric, cumulate ultramafic rocks layered gabbros, homogeneous gabbro, trondhjemite, albite, granite, diabase dike complexes, pillow basalts, cherts, and shales or altered equivalents--this is an ophiolite
- Rock masses bounded by faults, serpentine margins, rodingite (dense white rocks) suggests tectonic emplacement
- Rocks are lensoid masses of fault blocks made up of parts of the above sequences and occur in a setting where one can infer that the other rock types have been structurally removed (disembarked ophiolite)
- Occur at convergent margins, surrounding rocks are eugeosynclinal volcano-sedimentary units or island-arc volcanic sequences
- Ages cluster in the Jurassic-Cretaceous, in Ordovician-Late Precambrian; oldest are about 2 billion years in South Africa

Examine structure and stratigraphy of potential host rocks

Ultramafic cumulates

- Rocks present include dunite (olivine cumulate), harzburgite (olivine cumulate or olivine-orthopyroxene cumulate) wehrlite olivine-clinopyroxene cumulate) clinopyroxenite (clinopyroxene cumulate), feldspathic varieties of the above rocks, and interlayered gabbros in upper part of section
- Textures euhedral minerals in polikilitic or interstitial material-cumulate type textures--locally may be recrystallized
- Layered by rock types on scale of centimeters to hundreds of meters
- Gabbro, hornblende gabbro, pyroxenite dikes may be present
- By interlayering of ultramafic cumulates and gabbro grades upward into layered gabbros
- Olivine, Fo₉₃-Fo₆₈; clinopyroxene, Di₉₃-Di₆₅; orthopyroxene, En₉₃-En₆₈; spinel Cr₂O₃ = 33 to 60 percent
- Petrofabrics show an opposition fabric; crystals are randomly oriented in a plane of layering
- Fe-Mg minerals show iron enrichment upward

Examine to determine favorable local stratigraphy and structure

Peridotite Geochemically: High in Cr, Ni, Co, Mg. Geophysically: Magnetic highs and low associated with serpentinization

- Rocks present include harzburgite, dunite, ortho- and clinopyroxenite, chromitite
- Textures intergrown euhedral olivine, porphyroblastic orthopyroxene, kinked pyroxene (cleavage surface flashes in bands)--tectonite fabrics and recrystallization textures
- Layered by rock types, usually on less than a meter scale, layers vary from lenticular and irregular to moderately persistent
- Commonly contains folds (isoclinal and others) lineations, foliations
- Contain minor accessory chrome spinel
- Dunite, orthopyroxene, gabbro, diabase, and amphibolite dikes common
- Serpentinization ranges from little to complete
- Usually have a basal thrust surface against unmetamorphosed country rocks or dyothermally metamorphosed rock
- Thrust zone can contain serpentine, ultramafic mylonites, Greenschist to amphibolite facies metavolcanic and meta-sedimentary rocks
- Grades upward into ultramafic cumulates, upper contact is made by ultramafic cumulates
- Olivine, Fo₉₃-Fo₉₄; orthopyroxene, En₈₈-En₉₅ in a given ophiolite Fo and En vary by about 3 percent
- Other accessories, amphibole and plagioclase uncommon
- Olivine may have bimodal size distribution; bent cleavage in orthopyroxene common

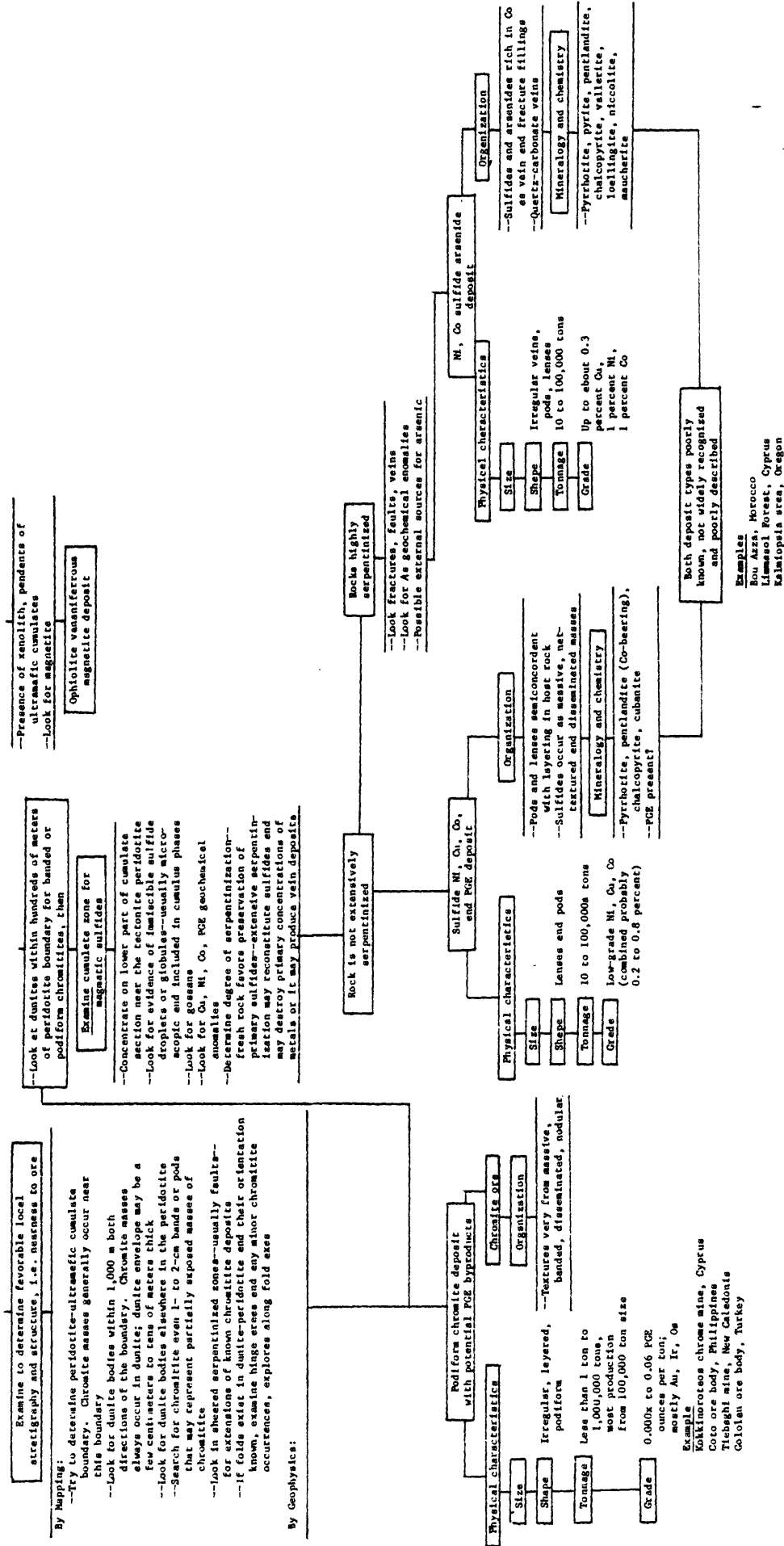
Weathering yields placers rich in Os-Ir alloys, low in Pt and Pd. Soils rich in Ni, Co, Cr (laterite)

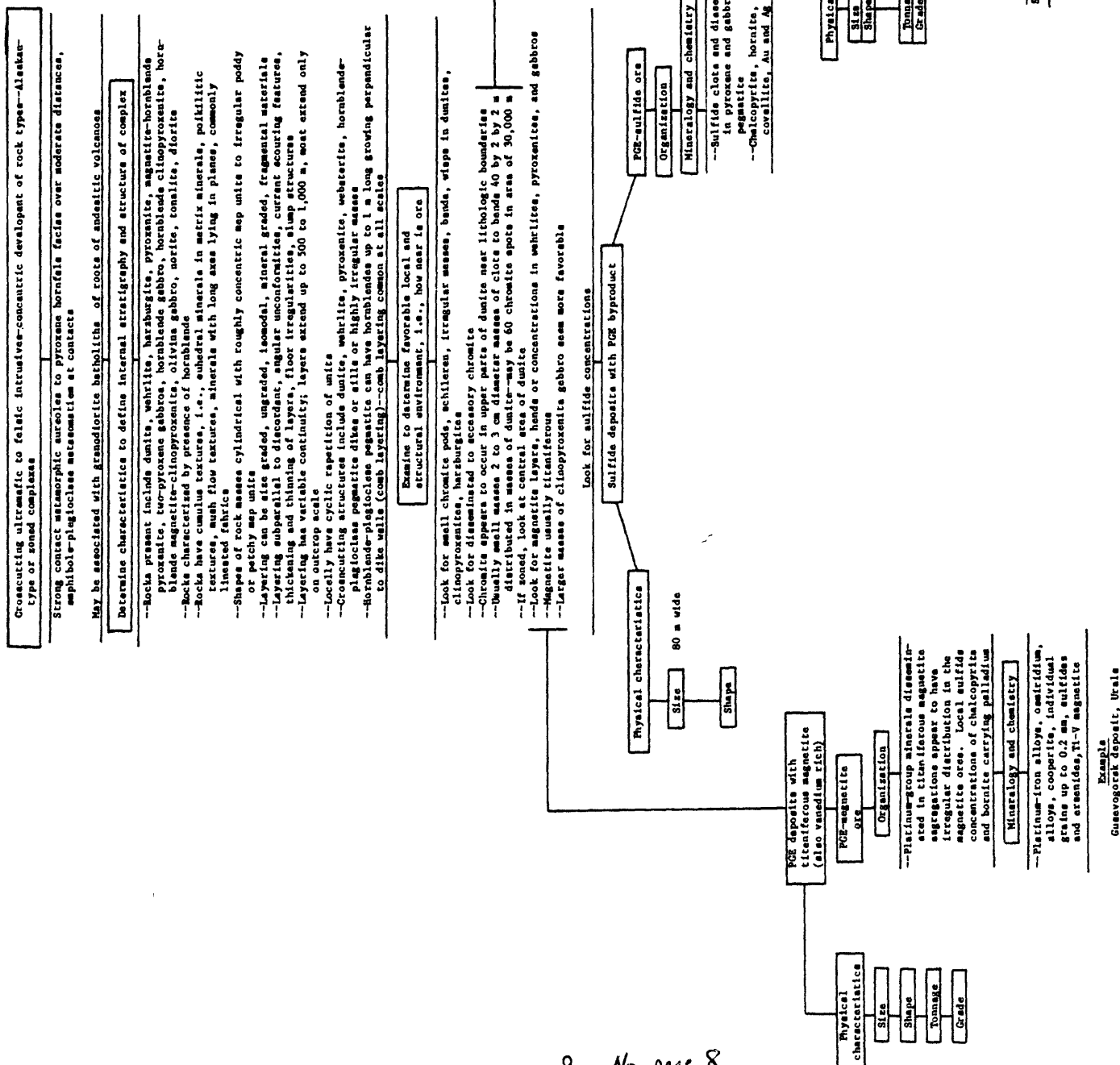
Gabbros

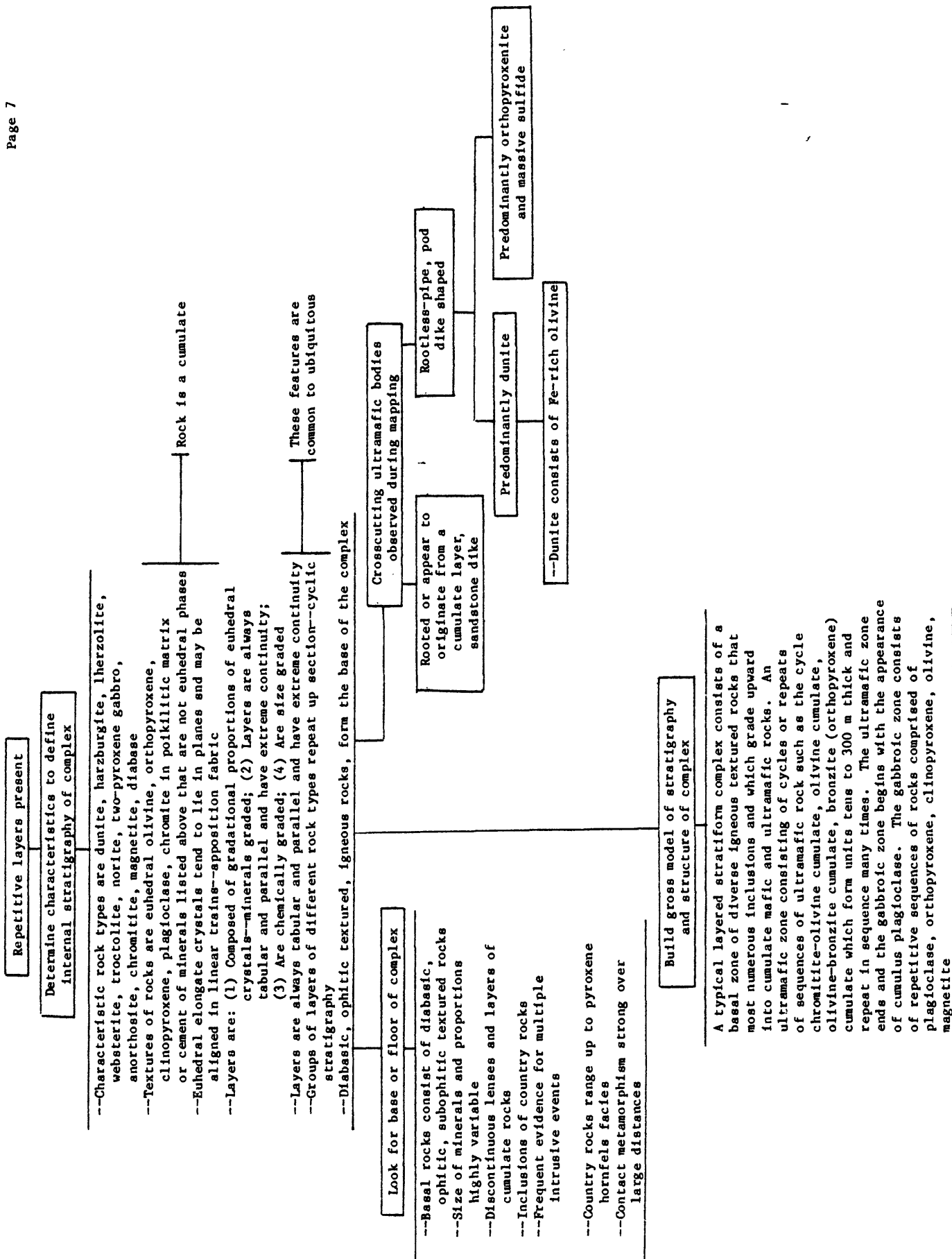
- Rocks present include two-pyroxene gabbros, norite (minor), troctolite albite granites, diorites, hornblende gabbros
- Bottom of section layered and has cumulate textures
- Top of section predominantly homogeneous gabbros
- Diabase dikes common and increase toward top
- By increasing amounts of dikes passes into dike complexes with gabbro screens into mainly dikes (sometimes sheeted)
- Mg/Mg+Fe of ferromagnesian minerals = 0.5-0.75; plagioclase An₄₅-An₇₅; amphibole pargasitic; accessories magnetite, sphene, epidote, apatite, ilmenite
- Pyroxene-rich gabbros may be altered to a hornblende diorite with pseudigneous texture, may locally grade into original igneous rock

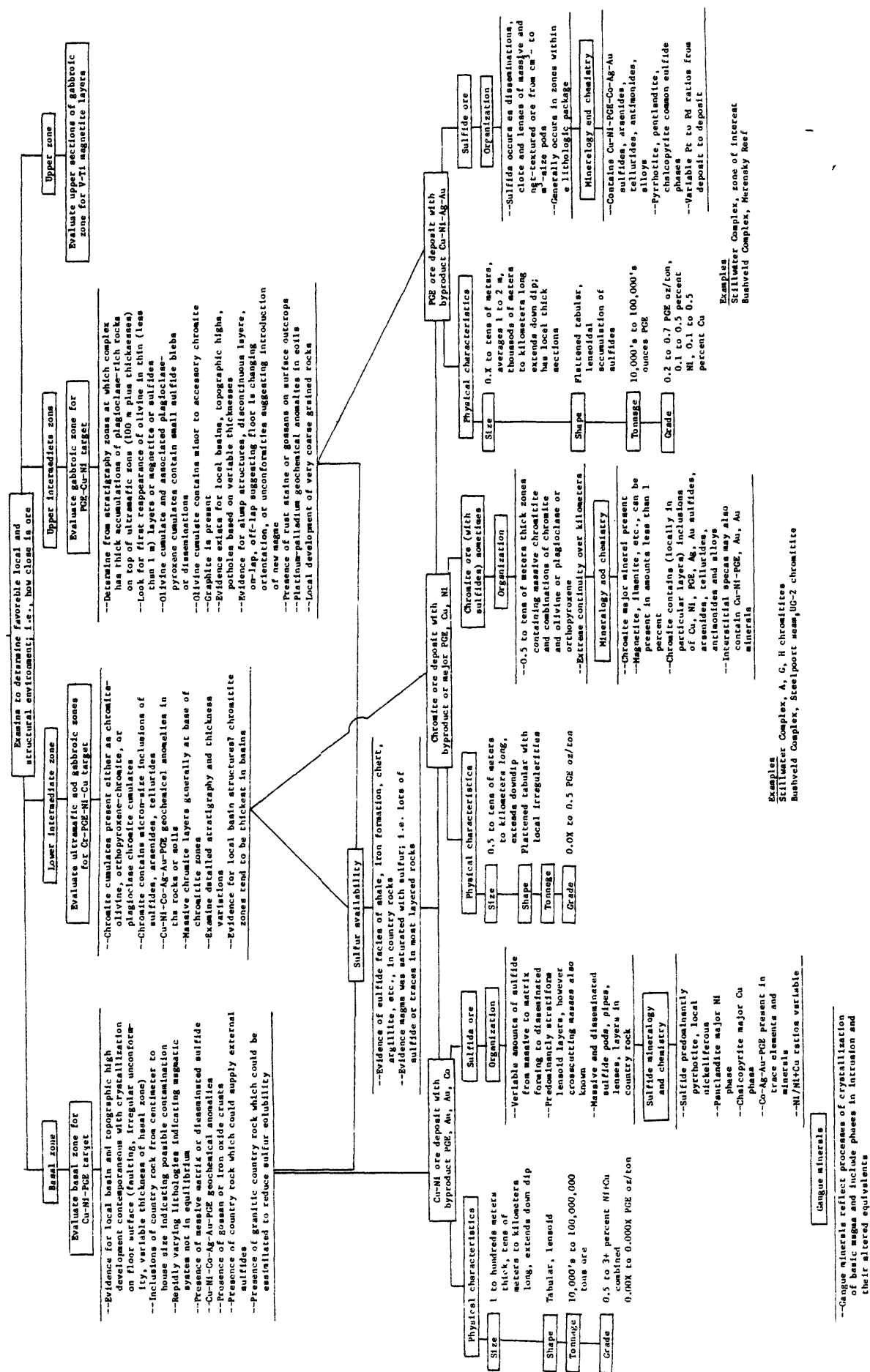
Examine crosscutting bodies of hornblende gabbro for favorable local ore environment

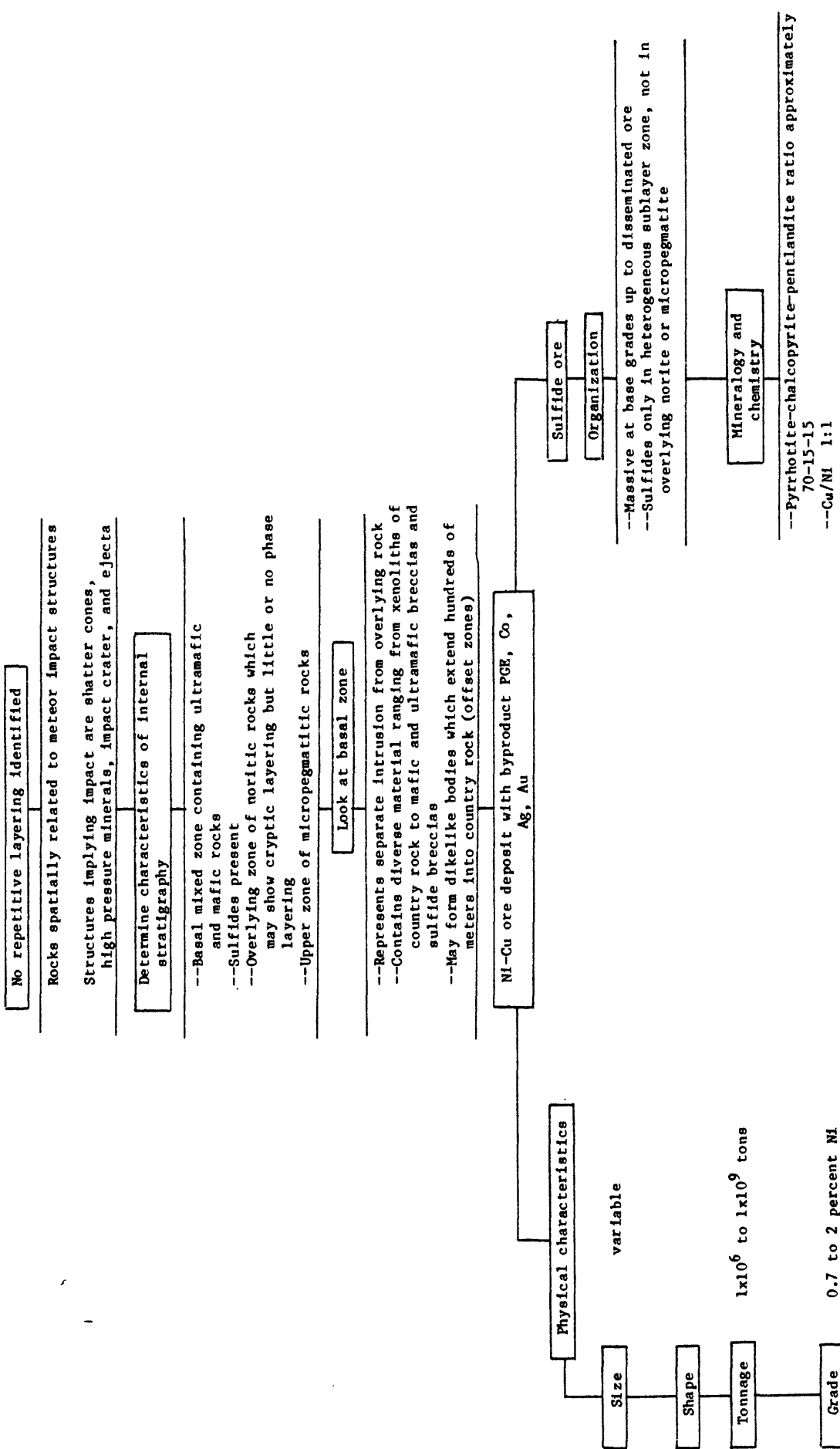
Pillow basalts and shales. See Cyprus massive sulfide models











Example
Sudbury

MAGMATIC NICKEL SULFIDES

By

Michael P. Foose

Magmatic nickel sulfides make up a relatively straightforward class of deposits. Although different types exist, remarkably similar features are common to most occurrences. These features are described below and may be taken as a general model for this class of ore deposit. Following this general discussion are descriptions of important subgroups of deposits.

General Features

Magmatic nickel sulfide deposits form within mafic and ultramafic rocks when the magma becomes saturated with sulfur, thus allowing an immiscible sulfide liquid to form. These sulfides form globules which, like rain drops, coalesce and fall to the bottom of the igneous body. The transition elements, including nickel, much prefer to form chemical bonds with sulfur than with oxygen (they are chalcophile) with the results that sulfide droplets may concentrate these elements by a factor of 100 to 1,000 over their levels in the host magma. Nickel ore deposits can be formed when concentrations reach about 10,000 ppm which is approximately four times the value of typical mantle material.

Therefore; magmatic nickel sulfide deposits are in mafic and ultramafic intrusive and extrusive rocks and are concentrated towards the base of the igneous body. These are the principal rules employed in looking for nickel sulfide deposits; exceptions exist, but they are relatively few in number.

The magma was saturated with sulfur early in its crystallization history. Early separation of immiscible sulfide liquids is required in order to collect metals from the melt before they become locked up in silicates. Physical evidence which can be looked for to establish this criteria are: (1) the presence of immiscible globules enclosed in silicates (mostly seen in thin section) and the presence of matrix sulfides that are molded around early cumulate grains. Chemical evidence to look for are contents of nickel in olivine that are lower than normal for grains of that Fo composition. These low-nickel values may indicate that nickel has partitioned into a sulfide phase before olivine crystallized.

Most nickel sulfide deposits occur in rocks older than 1,800 m.y. This may be due to changes in the geothermal gradient which could cause less sulfur-rich magmas to form as the earth became younger. In any event, older rocks are the best target areas.

Sulfide mineralogy is predominantly pyrrhotite, chalcopyrite, and pentlandite.

Sulfides are often concentrated in footwall depressions; often these are fault-bounded basins that developed during magma emplacement.

Deposits often show gossans and have a strong Cu and Ni geochemical anomaly.

Remarkably successful, if not simple-minded, explorations have been undertaken with these general tools. The procedure is to establish the presence of a Precambrian ultramafic or mafic body, determine where its base is located, look for gossans or other geochemical and geophysical anomalies, and then examine anomalous areas for immiscible sulfides.

The saturation of the magma with sulfur is an essential step in forming magmatic nickel deposits and may be accomplished by several mechanisms. Archean deposits, which are the most abundant, appear to be mostly associated with magmas that contained high concentrations of magmatic sulfur, and which became sulfur saturated during the normal cooling and crystallization of the melt. Saturation of sulfur in most younger intrusions, however, appears to be largely the result of the addition of sulfur from sulfide-bearing country rock or the assimilation of siliceous material by the magma which, in turn, reduces the magma's ability to hold sulfur. Thus locating sites where sulfide-bearing or siliceous units could be assimilated by mafic and ultramafic magmas can be important additional steps in locating sites favorable for magmatic sulfide deposits.

Specific Types of Nickel Sulfide Deposits

Several different types of nickel sulfide deposits are described below. Most attention is given to those which I feel have the greatest potential for new discoveries in the United States. All exhibit the "general" features listed above.

Layered intrusions.--Basal zones of large layered intrusions emplaced in stable cratons have traditionally been considered the most ideal targets for nickel sulfides. Examples are the Stillwater Complex, Montana, and the Bushveld Complex, South Africa. Because most large complexes of this type have already been identified, prospected, and reported on, there seems to be little point in developing a model to prospect for these bodies. Within existing complexes, basal parts of intrusions where sulfur contamination or silica addition may have occurred and where footwall depressions exist which could hold sulfides are still favorable target areas.

Sudbury, the world's largest nickel sulfide deposit, shares features in common with most layered intrusions and, in fact, provided the inspiration for most exploration in layered complexes. It, however, also shows many unique features which suggest that it be placed in a separate class. In any event, the events, including meteor impact, which formed Sudbury are so unique as to make construction of a "Sudbury" model a mostly academic exercise.

Komatiitic nickel deposits.--Nickel deposits associated with mafic and ultramafic lavas and subvolcanic feeders represent major targets for domestic exploration. Most are associated with a suite of rocks called komatiites. These rocks and the deposits they contain have been identified only relatively recently (early 1970's) and currently numerous komatiitic nickel deposits are being worked in Canada, Australia, and southern Africa. Komatiite associated deposits have not yet been found in the United States.

Precisely how komatiites are defined is the subject of much debate. I prefer the definitions of Arndt et al (1977). Critical elements are: (1) the presence of skeletal olivine and pyroxene which makes a distinctive texture called spinifex, and (2) relatively low TiO_2 and Al_2O_3 values for a given $FeO/(FeO+MgO)$. Deposits associated with these rocks may be grouped into those that are Archean and those that are Proterozoic. Younger deposits are not known.

Archean komatiitic deposits.--Nickel sulfides concentrate in the basal part of ultramafic flows, subvolcanic pipes, and shallow intrusions. Rocks which host these deposits have $MgO > 35\%$. These deposits always are in greenstone belts. Commonly, the greenstone belt shows cyclic sequences with ultramafic volcanics at the base and acidic material at the top. In these cases, the lower ultramafic material in cycle is the most favorable site for nickel sulfides, although sulfides may also occur within overlying cycles. Flows associated with sulfides often were extruded while the area was being deformed. Fault-bounded depressions provide sites into which sulfides were "washed". Deposits often lie on the flanks of large domal structures which are cored by granite; concentrations of deposits usually occur around the dome at the same stratigraphic level. High-iron tholeiites often are interlayered with the komatiitic rocks. There also is often a spatial association of magmatic sulfides with footwall rocks composed of chemical sediments (mostly iron formation), and there is an unexplained association of many deposits with occurrences of gold.

Examples of Archean komatiitic deposits are the Langmuir deposit in Canada and the Kambalda district in Australia. Favorable targets for domestic deposits occur in the Archean greenstone belts of Michigan, Wisconsin, and Minnesota.

Look for Archean greenstone belts containing spinifex-textured rocks of komatiitic compositions. Prospect the basal parts of the most MgO -rich rocks.

Proterozoic komatiites.--The internal features of Proterozoic komatiitic deposits resemble those in Archean deposits. That is, they occur in flows and shallow-intrusive systems within spinifex-bearing rocks. However, the regional setting of these deposits may be distinctly different from the better known Archean occurrences, with the result that favorable areas may be overlooked in regional resource assessments.

Unlike the Archean occurrences, Proterozoic deposits are not necessarily in greenstone belts. Many are hosted in volcanics which make up layers or lenses within thick sequences of pelites (greywackes?) which are believed to have been deposited near an active continental margin. These deposits often lie on a prominent geophysical lineament that is defined either by aeromagnetism, or gravity or both and which is thought to represent a major crustal boundary. In Canada, for example, deposits occur along the boundary of the Churchill and Superior provinces. The country rock often contains abundant graphite. This association may be coincidental but occurs so often that it may be useful in exploration. However, the ubiquitous graphite also makes numerous good conductors which, in turn, make a location of sulfide-bearing layers by geophysical methods difficult. Deposits have been very successfully prospected for by tracing sulfide-bearing boulders back to their source area; a technique that has been made even more effective by using sulfide-sniffing dogs to locate sulfide-rich float.

Look for Proterozoic terrains with thick greywacke sequences that have interlayered volcanics. Identify komatiites within these volcanic units. Look for graphitic and/or sulfidic country rock. Examine area (if glaciated) for sulfide-bearing float. Look for deposits in most MgO-rich volcanic parts.

Examples are the Thompson district in Canada and the Skellefte district in Sweden. Favorable target areas in the United States are in Michigan, Wisconsin, Minnesota, and North Dakota.

Rift-related nickel deposits.--Nickel deposits occur in tholeiitic volcanics and plutonics that were emplaced in zones of active rifting. Favorable rifting environments may be recognized by long linear gravity highs which indicate the presence of mafic intrusions (Ex: Midcontinent gravity high), the 120° intersection of major zones of rift-related normal faulting (Ex: Lake Superior area), and outpourings of rift-related flood basalts or other volcanics. The presence of an external sulfur or rock that could contaminate the magma with silica are additional features which appear necessary to form these deposits. Unlike most other nickel sulfide occurrence which are usually older than 1,800 m.y., deposits as young as Triassic have developed in some rift systems. These deposits may be subdivided into those that occur in plutonic rocks and those which occur in volcanics or shallow intrusives.

Plutonic deposits.--Nickel sulfides in rift-related plutonic complexes resemble those which occur in most large stratiform complexes. They are concentrated in the predominantly mafic basal zones of the intrusions. These zones lack a coherent internal stratigraphy and contain numerous inclusions of both country rock and diverse clasts of ultramafic rocks which presumably represent inclusions of unexposed and more ultramafic parts of the intrusive complex. Unlike most stratiform complexes, these intrusions generally lack well-developed rhythmic and cryptic layering. Sulfides concentrate near sulfide-bearing or siliceous country rock or large xenoliths of country rock. Sulfur isotopes that are heavier than normal magmatic values show that sulfur addition has been important in forming the ore deposit. Sulfides are commonly concentrated in fault-bounded depressions that developed during magma injection.

Look at basal parts of rift-related intrusive complexes where rocks occur in contact with sulfide-bearing or siliceous country rock and where footwall depressions are present.

Examples: Duluth Complex, Minnesota is best known occurrence; Midcontinent gravity high contains other target areas.

Volcanic and subvolcanic rift deposits.--Rift-related flood basalts may host important occurrence of nickel, copper, and PGE. I feel that these are an extremely important group of deposits and represent an environment which has received little attention in the United States. Unfortunately, an absence of detailed information exists for these deposits largely because of their exclusive occurrence in the U.S.S.R.

The deposits occur in flood basalts associated with a major episode of crustal rifting. Flows and sills which contain sulfides are typically between 30 to 350-m thick. All appear to be tholeiitic. The flows and sills were

emplaced during periods of active rift-related faulting, and sulfides are concentrated in basal fault-bounded depressions into which they have been "washed". An external source of sulfur appears to be necessary. Typically, this sulfur occurs in anhydrite beds which are part of an evaporite sequence that developed in restricted basins that form during the early stages of crustal rifting. Sulfur isotope studies confirm that most of the sulfur is nonmagmatic.

Look for flows and shallow intrusions emplaced during rifting that are associated with evaporite deposits or other sulfur-rich country rocks.

Examples are the Norilsk deposits in the U.S.S.R. which are of Triassic age. Favorable locations in the United States are the Triassic rift system in the eastern U.S., and the Keweenaw rift basalts that are part of the Midcontinent rift system.

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STRATIFORM CHROMITE

By

Bruce R. Lipin and Norman J. Page

The stratiform chromite model is based on the Stillwater complex, Montana.

Other deposits to which description applies:

Great Dyke, Zimbabwe; Bird River complex, Canada

Attributes

A. Tectonic/stratigraphic setting:

1. Archean shield areas--cratonic
2. Intrusion of the complex into a volcano-sedimentary unit or granite gneiss.
3. Tilted, folded, and faulted by later events.
4. Within the stratiform complex, chromitite zones occur in repetitive layers in the lower third of the complex.

B. Physical/chemical setting:

1. Wallrock is dunite, harzburgite, pyroxenite or anorthosite with 1-5% chromite. The texture is cumulate with adcumulus olivine growth on originally-settled grains or poikilitic texture with postcumulus minerals surrounding the accumulated minerals. Less common are granular-textured rocks with 2 cumulate silicates. Pegmatoid zones may be found in the footwall.
2. Serpentinization in the olivine-rich wallrocks may be 0-100%. Secondary magnetite and/or ferritchromite may be present. No particular pattern of serpentinization with respect to the chromite deposits is evident.
3. The ore consists of chromite with (in order of abundance) olivine, serpentine, orthopyroxene, plagioclase, and clinopyroxene. Trace minerals are biotite, hornblende, sulfides, magnetite, and chlorite. Textures are varied. Massive chromitite is equigranular. Other textures consist of chains of chromite surrounding much larger olivine or pyroxene grains. Olivine or plagioclase commonly poikilitically enclose chromite.
The chromitite zones generally follow a sequence consisting of a massive chromitite layer at the base grading up to alternating olivine-chromite and chromite layers upward in the zone. The number and thickness of the alternating layers varies from zone to zone and laterally with a zone.
In any given area of the complex, olivine and chromite compositions vary fairly regularly with respect to stratigraphy. Cumulus chromite and olivine in the footwalls of each cyclic unit show a steady decrease in iron from the lowest cyclic unit, Number 1 up to Unit 11. Thereafter from Unit 11 to 15 olivine and chromite show an increase in iron content (see table).
4. Fluid inclusions--not applicable

Cyclic unit (chromite zone)	Mg/Mg+Fe ²⁺ olivine in olivine cumulate	Mg/Mg+Fe ²⁺ chromite in chromite cumulate
15 (K)	.832	.486
14	--	--
13 (J)	--	.437
12 (I)	.840	.499
11 (H)	.846	.561
10 (G)	.838	.530
9	.844	--
8 (E)	--	--
7	.835	.500
6	--	--
5	--	--
4	--	--
3	.829	--
2 (B)	.820	.374
1 (A)	.815	.374

Cr/Cr+Al+Fe⁺³ doesn't show a systematic change but varies from 0.4 to 0.65

5. Textures, chemistry, and relationship to wall rock has been little affected by events after deposition. Evidence of magmatic sedimentation such as graded bedding, crossbedding, and cut-and-fill structures are all preserved except at highest grades of metamorphism.
6. The chemistry of the ore, gangue, and wallrock reflect the process of crystallization from a basic magma. The fact that some of the cyclic units and the chromite layers they enclose can be traced for miles suggests that the triggering mechanism for chromite precipitation was felt simultaneously throughout the magma chamber.
7. Geochemical signature--placer deposits may be useful.
8. Isotopic signature--none.

C. Ages:

The chromitites and their wallrocks were deposited during the same magmatic event. Ages on the stratigraphically-higher norites and gabbros are greater than 1.9 b.y.

D. Geophysical signature:

There are large, positive magnetic and gravity anomalies associated with the Stillwater complex. However, no geophysical signature specific for chromite deposits is known.

E. Average grade of the chromitite zones ranges from 7 to 55% Cr₂O₃. With few exceptions, each zone maintains grade laterally within narrow limits.

F. While the grade of each chromitite zone doesn't vary much laterally, thickness may vary from 0.5 to nearly 10 m. Of course, tonnage will vary with thickness.

G. PGE's and Ni-Cu sulfides are the only other commodities associated with chromite zones.

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KIMBERLITES OF CONTINERMINOUS UNITED STATES

by

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Kimberlites are rocks of unusual alkalic ultramafic petrology that occur in small diatremes, dikes, and sills. The largest diatreme known is about .80 km (.5 mi) across (De Beers geologist, oral communication, 1965). Kimberlites are one of the rarest rock types, even when compared to serpentinites, carbonatites, layered ultramafic complexes, and arnorthosites. Despite its volumetric insignificance, kimberlite is nonetheless a rock of major economic interest for diamonds and pyrope garnet gems. Many are also very useful in studying the petrology of mantle rock inclusions.

Definition: Kimberlite is a serpentinized carbonate-rich mica or basaltic alkalic peridotite with porphyritic texture, containing inclusions of many rocks from limestone through ultramafic rocks to eclogite. Most kimberlites are breccias, particularly those containing diamonds. A kimberlite may or may not contain diamonds, and only a very few contain economic diamonds. Kimberlite contains high pressure minerals such as green chrome or jadeite diopside, magnesium-rich (iron-lean) ilmenite, olivine, phlogopite or magnesian biotite, chromite, pyrope, chrome pyrope, and pyrope almandine, enstatite, hornblende, perovskite, and apatite. Much calcite, some of mantle origin as determined by strontium isotope ratios, is characteristic. Diamonds, where present, are sparsely scattered through the groundmass; some are in the eclogite nodules. Massive kimberlite is known without many inclusions of country rock or mantle xenoliths and can be subdivided into basaltic and micaceous varieties, the latter grading into alnoite.

Kimberlite and related alkalic rocks are found mostly in shield areas, cratons and rifted platform areas and plateaus. Less commonly, they are found in folded and thrust areas such as in Pike County, Arkansas. Locally they are found as clusters of pipes and dikes along deep-seated lineaments, at the intersections of lineaments and along major joints, especially those of tensional origin. They cluster in and along rift valleys and fracture systems spreading from them as in the African rift valley system or in the Mississippi River Embayment. Others lie along strike-slip faults and their associated fold crests. In many kimberlites the rock is a mass of intrusive fluidized breccia largely altered to serpentine, chlorite and carbonates; some of the carbonate may be mantle derived; some is also derived from the limy wall rocks intruded. Fluidization textures are prevalent and clasts from below and above are common. For example, the kimberlite near the Colorado-Wyoming State line contain masses of Silurian fossiliferous limestone, the nearest remaining outcrops of which are more than 160 km (100 mi) away. The same diatremes are full of mantle-derived pyrope and chrome diopside, and eclogite, indicating that the intrusive process included a vast surging and fluidizing rich in gas and water or water vapors. It is during this process that much of the serpentine is formed.

The intrusive kimberlite breccia contain from 20 percent to nearly a 100 percent rock fragments. In a few only a small fraction of the ground mass or rare clasts may be igneous. Some of these may contain diamonds (C. F. Davidson, oral communication to Heyl 1965). One or more stages of kimberlite

breccia in a single pipe are common. Breccias are less common in dikes, but are present in the two dikes in Pennsylvania and several in New York. Kimberlite extrusive breccia in mass usually contain 60 to 90 percent fragments (Dawson, J. M., 1967, p. 244 in Wyllie's volume) of kimberlite and country rock. The texture is fragmental; flow textures are absent or in broad bands. They are named according to the dominant type of kimberlite, basaltic or alnoitic.

The main unaltered, primary minerals diagnostic of kimberlite are chrome diopside, pyrope or related garnets, olivine (partly serpentized), phlogopite or Mg-biotite, magnetite, magnesium rich-iron, lean-ilmenite and perovskite; and, of course, diamonds. It is these minerals which are looked for in residuum and stream sediments (even ant hills) by prospectors for kimberlites. Diamonds decrease in quantity with depth in most pipes, so the upper parts of the pipes are the most promising. "About 1 pipe in 70 pipes may contain commercial quantities and qualities of diamonds in Africa" according to some diamond company geologists (oral communication to Heyl, 1964). The pipes do not have to contain more than a small percentage of igneous rocks to bear diamonds, and only one or two of the main diagnostic primary minerals listed above need to be present to be of interest for diamonds. Gem pyrope is also recovered from the Czechoslovakia pipes and from those in northeastern Arizona and the Nemaha Uplift in central Kansas. A very large group follow the Rocky Mountain Front, its foothills, and in the domes, anticlines and faults extending out from the structural front such as the Hartville uplift connecting the Rocky Mountains with the Black Hills. Very uncommonly they are found in sills in this region.

Kimberlites form funnel-shaped pipes flaring outward upward. They are usually derived from simple pipes at depth, or from enlargements or blowouts above and along dikes. They may be found in almost any kind of wall rock (one is even known to cut thick beds of salt in the Salina Formation). In Africa relatively recent volcanic mounds or cones of ash of low heights are known.

Very little alteration is found in the wall rocks around them. The temperature of intrusion near the surface is very low, estimated by Watson (1967, p. 280, 320-321) in Wyllies (1967), volume on "ultramafic and related rocks" from the narrow reaction zones in coals, salt beds, limestone and shales as from 40° to 600°C. Generally such baked zones are less than 0.3 of a meter thick. Fragments of limestone may have thin marbled rims a few mm to a cm wide and coals may be coked outward for a foot. This low temperature near the surface may be the result of sudden exhalations of gas and steam.

Gangue minerals and groundmass minerals are of great variety and include serpentine, orthopyroxene, tremolite or actinolite, calcite (some mantle derived by strontium isotope ratios), magnetite, zeolites, apatite, fine-grained phlogopite, pyrochlore, potash nepheline, moissanite (silicon carbide), sphene, rutile, anatase, dolomite, almandine, hematite, brucite, pyroaurite, pyrite, marcasite, barite, sphalerite, galena, chalcopyrite, fluorite, millerite, celestine, gypsum, baddeleyite (ZrO_2), humite, magnesite, vermiculite and chlorite, monticellite, and soda amphiboles.

The analyses of whole rock kimberlites given here are quite representative of most kimberlites world wide. The trace element patterns (elements and relative quantities) shown in the listing are typical and

characteristic of most United States kimberlites, which are remarkably uniform, from all the analyses I have made to date from Lake Champlain to Colorado.

Analyses of Kimberlite

	I ¹	II ²
SiO ₂	27.81	34.73
TiO ₂	1.63	1.62
Al ₂ O ₃	3.40	2.88
Cr ₂ O ₃	0.13	---
FeO ₃	5.40	6.10
FeO	2.82	3.13
MnO	0.12	---
NiO	0.14	---
MgO	25.53	31.41
CaO	12.21	5.79
Na ₂ O	0.33	0.33
K ₂ O	0.66	1.17
P ₂ O	0.50	1.06
H ₂ O+	---	9.20
CO ₂	---	2.58
Loss on ignition	<u>19.42</u>	<u> </u>
Total	100.10	100.00

¹Kimberlite of Yatvtia Siberia. Average of 339 analyses.

Quoted from Robrievich et al, 1964.

²Average kimberlite, excluding U.S.S.R. occurrence,
(Daly, R. A., 1933)

Trace elements common and distinctive of kimberlites⁴

	I ¹ ppm	II ² ppm	III ³ ppm
Ti	20000	10000	7000
Mn	1500	1500	700
Ag	0-1 (est)	0-1 (est)	0-1 (est)
Ba	1000	1000	500
Co	100	150	30
Cr	3000	1000	700
Cu	70	50	70
La	100	100	30
Mo	5	7	N
Nb	50	30	70
Ni	500	500	300
Pb	---	1	20
Sc	20	7	7
Sr	150	300	150
V	200	150	70
Y	20	10	10
Zr	70	100	70
Ce	500	500	100
Yb	2	1	1
Ga	N	1	10
F	1500	1000	not analysed

¹Elliot County, Kentucky, main Kimberlite pipe body, whole rock. Analyst J. L. Harris 1970. Sample collected by J. L. Jolly and A. V. Heyl 1965.

²Masontown, Pennsylvania dike. Analyst J. L. Harris 1970. Sample collected by M. R. Brock and A. V. Heyl 1963.

³Pipe near Flagstaff Mountain, west of Boulder, Colorado. Analyst N. C. Conklin 1981. Sample collected by A. V. Heyl 1981.

⁴Major elements not listed. Other elements that are not listed were not found. N equals not found where shown; either absent or below the limit of detection.

Inflammable gas has been encountered in South Africa and Siberian kimberlites. Some drill holes flamed for days. C. F. Davidson (1967, p. 256) in Wyllies' volume gives the quantitative composition of the gas from the Udachnaya pipe as follows: 50 to 90 percent H₂, 30.4 percent CH₄, 12.8 percent N₂, 3.7 percent C₂H₆+, 1.9 percent O₂, 0.032 percent He, 0.016 percent Ar, and 1.9 percent undetermined hydrocarbons. Sodium chloride brines (150 g per liter) were encountered in the same pipe presumably from Cambrian country rock. The average fixed water content of kimberlite pipes is 7.7 percent and the CO₂ content is much in excess to that in non-alkaline, ultramafic rocks.

The ratios of $\text{Sr}^{87}/\text{Sr}^{86}$ of kimberlite ranges from 0.705 to 0.729 (average 0.712 in 14 samples) and carbonatites average is 0.7032 (Dawson 1967, p. 224 in Wyllies' volume). Granites, in contrast, give a range of values between (0.740 and 1.003) according to their age. Carbon isotope of Russian kimberlites give $\text{C}^{12}/\text{C}^{13}$ ratios between 89.45 and 89.63 (Vinogradov et al 1965) which suggests to Dawson that the Kimberlites and diamonds have a common origin.

Kimberlites can be of almost any age. Precambrian ones are known in Canada and the isotopic ages of a number of U.S.A. kimberlites determined by Zartman and others (1966) ranged from Ordovician to mid-Cretaceous.

Many kimberlites show strong positive magnetic and gravity anomalies to their wall rocks, but a few have almost no magnetic anomaly. The bodies are usually so small that only tight local ground surveys are useful, and thus the bodies cannot be easily prospected by these methods.

Because of the carbonate and serpentine matrix, most bodies do not outcrop well. In fact, most do not crop out at all. In southeast Missouri alone about 100 bodies of kimberlite and related alkalic rocks are known. Less than 70 outcrop, usually poorly, and estimates have been made by the author that for every one known, 5 to 10 exist that are not exposed and are as yet unfound.

Prospecting is done by surface outcrop searches, also by panning of stream sediments for pyrope, ilmenite, chromite, chrome diopside, and even for diamonds. In the United States chrome diopside travels the least distance, and chromite the farthest, maybe a few kilometers.

First sampling is generally by mass samples from pits or trenches and then grinding and gravity concentration. Second stage sample of pipes with diamonds uses 15,000+ tonne samples. If gem diamonds accompany the industrial diamonds then a third stage using 25,000 ton samples is generally required to determine which pipes are economic. The average grade is not generally published, but probably is in the range of a carat per tonne. By-products or possible ones would be pyrope garnets as gems, and in a few pipes, chromite and titanium minerals.

Interest in prospecting for kimberlites and testing them for diamonds is widespread and a major interest among many mining companies in the United States in 1980-1981.

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A GENERALIZED EMPIRICAL MODEL FOR PORPHYRY COPPER DEPOSITS

By
Dennis P. Cox¹

Regional Settings

Favorable regional environments are:

- Continental margins or fragments of margins where igneous intrusive rocks are abundant and where there is evidence of strong faulting contemporaneous with intrusion.

- Island arcs or eugeoclinal environments intruded by igneous rocks and cut by many faults.

- Mesozoic and Tertiary intrusive rocks are most favorable possibly because of erosion and denudation of crustal rocks and destruction of near-surface deposits produced in older rocks, or because of favorable plate tectonic interactions in those periods. Deposits may be in rocks of any age. Low-grade porphyry deposits are found in Archean greenstone belts in Canada in granitic rocks coeval with the volcanic sequences that contain massive sulfide deposits.

- In southern Arizona, a region affected by two distinct magmatic episodes. The earlier episode is more likely to have associated deposits. The later episode may be barren because Cu in the lithosphere was depleted by the earlier event.

- In a region having a clear relation to a paleosubduction zone, i.e. Puerto Rico or Panama, deposits may be associated with igneous rocks produced during a cessation or abrupt change in subduction activity. Deposits may be related in time to rifting episodes in a mainly subduction style continental margin. Deposits may be more common near major transverse structures or lineaments such as would occur in a segmented upper slab over a subduction zone.

- Deposits are believed to form during the waning, fumarolic stage of stratovolcano development. Caldron subsidence and eruption of ashflow sheets disrupt the accumulation of volatiles and metals and destroy any metal concentrations already formed.

Favorable Rock Associations

Two rock associations must be considered: (1) the intrusive temporally, spatially, and genetically(?) related to the mineralization; (2) the host rocks for deposition of copper minerals.

The intrusive:

- (a) The ore-related intrusion may be one of a wide variety of rocks. Quartz-bearing intermediate composition rocks, adamellite, granodiorite, and tonalite, are most common. Some deposits are associated with monzonite or syenitic intrusions (Afton, B.C.).
- (b) Associations with potassium-rich granite are not known. Quartz-poor diorite or gabbro are rarely hosts (Black Mountain, Philippines).
- (c) Ore-related rocks usually have a porphyritic phase having a microgranular aphanitic quartz-feldspar groundmass with a texture similar to fine aplite (allotriomorphic aphanitic).

¹The author thanks R. H. Siltoe for a thoughtful review of this preliminary draft.

- (d) Under the hand lens, the groundmass resembles wet sugar.
- (e) Phenocrysts are usually closely spaced so that groundmass is difficult to see in the field.
- (f) In rocks of syenitic composition, groundmass may be composed of potassium feldspar only, here also with aplitic texture.
- (g) Ore-related intrusions are always passive. That is, their contacts show stopping, intrusion brecciation, and numerous dikes and apophyses. Conversely, synkinematic intrusions in zones of regional metamorphism rarely or never give rise to copper concentrations.
- (h) Intrusions of the "I-type" (Chappell and White, 1974) and "magnetite series" (Ishihara, 1977) rather than "S-type" and "illmenite series" are related to introduction of copper ore.
- (i) Stocks having a complex history of multiple intrusive phases are more likely to be associated with high-grade, hypogene copper deposits.
- (j) Breccias having sulfides and hydrothermal alteration silicates (biotite, sericite, tourmaline, etc.) are associated with some deposits (Cananea, Mexico).

Host rocks

The ore-related intrusion is commonly the host of copper mineralization (Bingham, Utah; Yerington, Nev.).

Pre-ore rocks that are good hosts for copper mineralization include:

- (a) Equigranular plutonic rocks of intermediate composition (Butte, Orange Hill, Alaska).
- (b) Mafic rocks including diabase (Ray, Vekol Hills, Ariz.).
- (c) Intermediate to mafic volcanic rocks. In these rocks, chalcopyrite occurs in veinlets and also replaces magnetite and mafic minerals (Safford, Ariz.). Thus leucocratic igneous rocks are usually not good hosts.
- (d) Limestone (Pima, Mission, Ariz.; Carr Fork, Utah).
- (e) Clastic rocks having calcareous cement (Copper Canyon, Nev.; Bee Creek, Alaska).
- (f) Carbonate rocks are in most cases, so receptive of copper mineralization that ore-related intrusions into carbonate sections maybe strongly depleted in copper (less than 0.2 percent Cu).
- (g) Rocks of various composition that are competent and closely fractured.

Alteration Guides

Rocks are altered in various ways over large areas around deposits. Where best developed, the alteration is pervasive, not just localized along a few fractures.

Abundant quartz in numerous closely spaced veinlets is a very strong indicator.

Abundant pyrite in numerous closely spaced veinlets is a strong indicator and is best developed in zones peripheral to a porphyry ore body.

Propylitic alteration marked by any or all of the following: chlorite, epidote, actinolite, calcite, pyrite, hematite. Veinlets of quartz are not usually abundant. May form an outer zone surrounding but not including the copper deposit. Most easy to detect in mafic to intermediate igneous rocks

and graywackes, this zone may be impossible to identify in areas of regional greenschist metamorphism.

Argillic alteration: Bleached white rocks marked by clay replacement of plagioclase and mafic minerals. Pyrite veinlets may be abundant. Break the rock and touch tongue to broken surface. If it is argillic, it sticks to tongue. Argillic alteration is probably mainly supergene in origin.

Advanced argillic alteration includes Al-rich minerals such as pyrophyllite and andalusite and is always hypogene.

Phyllic or quartz-sericite-pyrite alteration: Strongly favorable where it is pervasive. Feldspars are clouded or completely replaced by sericite. Pyrite is usually abundant.

Potassic or biotite-K feldspar alteration: Strongly favorable but it may be difficult to identify. Igneous biotite and hornblende are commonly replaced by fine randomly oriented biotite flakes. Fine biotite may occur in veinlets with sulfides or magnetite but without quartz. Potassium feldspar may form pinkish-tan sugary veinlets with vague outlines. Igneous plagioclase may be unaltered, or partially replaced by potassium feldspar, and(or) partially clouded by flecks of sericite. Volcanic rocks and diabase are altered to biotite hornfels, usually with abundant sulfides.

Because feldspars are stable in this environment, the rocks look fresh and break like fresh rocks. Potassic alteration is usually accompanied by intense quartz veining. Rocks in a potassic alteration zone are not necessarily richer in potassium than fresh rocks or sericitized rocks. Identification may be difficult in deposits where biotite is chloritized by post-mineralization meteoric(?) fluids (Ajo, Ariz.; LaVerde, Mexico; Tanama, Puerto Rico; Cerro Colorado, Panama). Confusion between chloritized-potassic and propylitic types of alteration can be a problem.

Relationship of Ore, Intrusive Rocks and Alteration Zones

There are important generalities that hold for most deposits:

Zonal relationships.--Copper ore is usually best developed in the form of a cylinder that may be closed at the top. Inside is a "barren core" having low-total sulfur content and low-copper grade. Outside, copper grade falls off and total sulfur increases producing a pyrite halo. The cylinder is characteristically centered around the ore-related igneous intrusive. Potassic alteration is commonly coextensive with the ore zone and barren core and grades outward into propylitic alteration.

This pattern may be distorted or destroyed by the presence of receptive wall rocks (well-fractured rocks with abundant mafic minerals or carbonate minerals). In these situations, the intrusive may be barren (Copper Canyon, Nev., Pima, Ariz.).

Time relationships.--The zoning described above is usually established early in the development of the deposit. As temperatures fall and ground water gains access to the system, phyllic and argillic alteration begins and migrates inward and downward through fractures in the system. Thus some samples or outcrops within the system may show multiple stages of alteration (i.e., pyritic fractures having sericitic alteration envelopes cutting porphyry having potassic alteration assemblages). Biotite in potassic assemblages may be more or less completely altered to chlorite during the later stages in some deposits.

In most deposits, copper ore distribution is independent of later stage alteration patterns because the late solutions did not dissolve and redeposit copper. In others (Butte is the best example), late solutions removed copper from the disseminated ore zones and redeposited it in high-grade veins having sericitic and advanced argillic alteration envelopes.

Not all of these alteration types are usually observable in any one locality because to some extent, alteration type is a function of depth in the porphyry system (advanced argillic-phyllic-potassic from surface to deepest part). Therefore, at a particular level of erosion only one alteration zone may be exposed.

Fluid Inclusions as a Guide

Fluid inclusions are samples of the hydrothermal solution(s) that passed through the rock at some time in its history. These samples are trapped and preserved in growing crystals of quartz and other minerals.

Observation of fluid inclusions in the course of routine petrographic study of rocks can provide clues to undiscovered deposits. The observations are easy to make. Select a quartz grain, use a 40X or 50X objective and substage condenser, and adjust the substage iris diaphragm to produce the desired contrast. Search for inclusions in which a meniscus between fluid and vapor can be seen.

Fluid inclusions that contain, in addition to fluid and vapor, daughter minerals such as halite, sylvite, hematite, or anhydrite are strongly diagnostic of copper ore nearby.

Ore zones: Inclusions rich in daughter minerals are abundant within most ore zones. This fact is useful in interpretation of strongly leached or saprolitically weathered outcrops where all copper minerals have been destroyed.

Core and root zones: Inclusions rich in daughter minerals are abundant in most barren core zones and, in the case of Ajo, Ariz., in the equigranular unaltered pluton that is believed to represent the root zone of the Ajo ore body. Exposed root zones and barren core zones do not necessarily mean that the ore body was eroded away. Porphyry deposits occur in tectonically active areas and many deposits are cut by faults of large displacement. If you see mineral-rich inclusions in a plutonic rock or unmineralized porphyry, suspect a downfaulted ore body hidden under postmineral cover nearby.

Ore zones in receptive wall rocks: Fluid inclusions may be poorly developed in mineralized wall rocks. Ore-related porphyries adjacent to such wall rock ore bodies, however, may be rich in inclusions with saline daughter minerals even though they are nearly barren of copper. Field relations may exist in which a mineralized sedimentary section may be hidden, the only clue to its existence being outcrops of intrusive rocks with mineral-rich inclusions.

Effects of Weathering

Porphyry systems, where they are exposed at the surface, give rise to a variety of visual effects. The more striking of these are almost always associated with a network of drill roads and bulldozer cuts at least in the lower 48 states. In systems or parts of systems having high chalcopyrite:pyrite ratio, crusts of malachite, azurite and chrysocolla are found in outcrops. Weathering of highly pyritic ore bodies produce low pH waters that often leach most of the copper out of rocks in the oxidized zone. Dark veinlets and smears of limonite with admixed hematite, the so-called "live limonite", having a dark-reddish-brown streak and veinlets of glassy, dark ("beer-bottle") limonite are good indications of copper ore in leached outcrops.

Less obvious are the widespread "color anomalies" produced by a combination of iron staining and acid bleaching of outcrops containing disseminated pyrite. These colors mark the pyrite halo which may extend many kilometers out from a porphyry mineralization center. Nearly all porphyry deposits have such a halo. Unfortunately, the opposite is not true.

Mineral and Metal Associations

Copper as chalcopyrite and more rarely bornite is associated with molybdenum as molybdenite or gold in the ore zone.

Silver, probably tied up with chalcopyrite, is a byproduct in most deposits. Tungsten, as scheelite(?), may occur in porphyry ore zones in certain areas (N. Cascades Washington; Sonora, Mexico).

Whether a porphyry copper deposit is moly-rich or gold-rich probably depends on the chemistry of the ore solutions. In deposits of low-total sulfur content where chalcopyrite occurs in association with magnetite rather than pyrite, gold is held within the ore zone and a gold-rich porphyry results. There is some evidence (from Helecho, P.R. and some Philippine deposits) that moly moves out of the ore zone into the wall rocks in such deposits. Deposits with abundant pyrite in the ore zone tend to be moly-rich. Any gold that may be present in the system is in peripheral vein deposits.

Porphyry systems disturb the geochemistry of large volumes of rock during their emplacement. Zonal patterns in mineralogy of small vein deposits and in rock and stream-sediment anomalies can be observed extending 10 km outward from some porphyry deposits. These patterns are generalized in the following table:

Mineral deposits	Chalcopyrite and sphalerite limestone replacement lenses	Enargite or other sulfosalts in veins	Galena, sphalerite veins and replacement bodies	Mn carbonate veins
Metal anomalies	Cu, Pb, Zn	Cu, Pb, Zn, As, Ag, Au	Pb, Zn, Bi, Ag, Au (Sn)	Mn, Ag, Au

Secondary dispersion of elements during weathering of porphyry systems depends on the pyrite content of the ore and presence of carbonate minerals in wall rocks. Abundant pyrite weathers to form low-pH waters that leach copper and carry it downward to be redeposited as chalcocite below the water table. Gold if present may remain behind producing a strong soil geochemical anomaly. The pH can be raised by the presence of limestone, or calcite in veinlets, and the copper fixed as carbonates and other oxides in the oxidized zone. In ores of low-pyrite content very little transport of copper may take place and outcrops may contain chalcopyrite and oxidized copper minerals.

Sillitoe has pointed out the possible existence of porphyry systems low in copper and low in sulfur, but rich in magnetite and gold. Such systems would present only weak iron and copper staining in outcrop and would be hard to detect. No such deposit has yet been found.

GEOCHEMICAL EXPRESSION

By

Maurice A. Chaffee

Porphyry copper deposits may show anomalies for a varying group of trace elements at one or more scales: (1) regional, (2) district-wide, and (3) intradeposit. The element suite related to a given deposit varies with a number of factors. Some of these factors include rock types in wall rocks, rock types in ore-related intrusions, primary ore-related mineral suite, weathering environment (past and present), present erosion level in deposit system, number of hydrothermal "pulses" in a given system, age of deposit, geographic location of deposit, and so on.

Information on the geochemical expression of porphyry copper deposits is presently limited but is slowly becoming available as geologists recognize the value that geochemistry can provide in the search for new deposits. Geochemical parameters based on several deposits in Arizona and Nevada are tabulated below.

Regional Geochemical Suite:

Cu	50-100 ppm	in stream sediment
Pb	50-100 ppm	in stream sediment
Te	100-400 ppb	in stream sediment

District-wide Suite:

Cu	>100	ppm	in stream sediment
Pb	>100	ppm	in stream sediment
Te	>400	ppb	in stream sediment
Ag	>0.5	ppm	in stream sediment
Au	>50	ppb	in stream sediment
Mn	<1000	ppm	in stream sediment
Zn	>100	ppm	in stream sediment
Mo	>5	ppm	in stream sediment
Ba	>3000	ppm	in heavy-mineral concentrate
Sr	>1000	ppm	in heavy-mineral concentrate

Intra-deposit Suite (zoned deposit, rock samples):

<u>Element</u>	<u>Zone where element has highest concentration</u>	<u>Ranges of concentrations for elements in all zones (ppm except Fe and S)</u>		
B	Barren Core	N(20)	-	200
Ba	"	70	-	3,000
Sr	"	30	-	700
Li	"	10	-	1,100
Cu	Ore-Zone	10	-	30,000
Mo	Ore-Zone or Ore-zone fringe	N(3)	-	1,000
Ag	Ore-Zone or Outer aureole	N(0.5)	-	15
Au	Ore-Zone or Outer aureole	N(.02)	-	0.4
C	Ore-zone Fringe	<(5)	-	100
V		30	-	300
Se	Pyrite Zone	<(0.1)	-	16
Fe	Pyrite Zone	0.3	-	10.0%
S	Pyrite Zone	(.01)	-	10.0%
Rb	Outer Aureoles	20	-	200
Te		N(0.1)	-	2
Au		N(.02)	-	0.4
Fe		0.3	-	10.0%
Pb		N(10)	-	1,000
Zn		N(5)	-	1,100
Mn		7	-	1,500
Tl		N(0.2)	-	4.2

Other ore elements such as Hg, As, Sb, Sn, and W are known to be related to some porphyry copper deposits but not enough reliable information is available to indicate their distributions and abundances relative to known ore zones.

Ratios of elements, such as Cu/Zn, Fe/Mn, Rb/Sr, and Cu(partial)/Cu(total) have been useful locally in defining zones around some porphyry deposits.

Under ideal conditions elements such as Cu, Mo, Zn, and Au in alluvial samples may be used to detect porphyry-copper-related mineralized areas some tens of miles downstream from source areas.

GEOPHYSICAL EXPRESSIONS OF PORPHYRY COPPER DEPOSITS, SOUTHWEST UNITED STATES

By
Calvin K. Moss

Efforts of exploration groups to characterize the magnetic expression of porphyry copper deposits have been largely unsuccessful. In a low percentage of deposits, the development of magnetite skarn is substantial enough to produce a magnetic anomaly. The simple presence of skarn minerals, however, is not sufficient cause for an anomaly.

Although a porphyry deposit may not produce a characteristic magnetic expression, it may lie in a more-or-less characteristic environment. The most common environment for a porphyry deposit is the flank of a magnetic high. The high may be caused by an intrusive body genetically related to the deposit, or by an intrusive body significantly older than the deposit.

Some porphyry deposits are seemingly emplaced in basement sutures represented by a contact between a Precambrian granodiorite and a less magnetic Precambrian rock. In that position the deposit is again situated on the flank of a magnetic high. This high might be sinuous, and tens of miles in length.

Porphyry copper deposits that are not located adjacent to a magnetic high are fairly common in the Southwest. They appear to represent a prevalent exception to the above generalization. However, some of these deposits--perhaps the majority--have been severed from their roots by a gravity slide or by a low-angle fault. Movement simultaneously displaced the deposit from the root source of an associated magnetic anomaly.

The IP expression of a porphyry copper system is more unique than are the expressions for other geophysical methods. The pyrite halo of a large porphyry copper system might be detectable as deep as 2,000 feet. Overlying conglomerates may contain interstitial clays of a particular kind and show an IP expression. Usually this effect can be identified as such, with proper field and interpretational procedures.

With conventional IP equipment, zones enriched in copper sulfides cannot be distinguished from those containing pyrite alone. Certain equipment designers make modest claims of success in the latter objective using equipment which measures IP phase parameters. Regardless of those claims, the simple identification of a concealed pyrite halo with IP can be an important step toward discovery of a porphyry deposit.

A resistivity expression is normally present at a porphyry copper deposit. Inner zones of alteration may show a decrease in apparent resistivity by a factor of ten or more, relative to unaltered rocks. The use of the resistivity expression in conjunction with the IP expression has been valuable in identifying economic sulfide zones that have relatively low concentrations of total sulfides.

Porphyry copper deposits having sulfides within a few hundred feet of the surface will probably exhibit an EM expression if appropriate techniques are used. Conductors are stockwork sulfides, predominantly pyrite. These may be

augmented by clay conductors in fracture zones. The presence of an EM anomaly was of crucial importance in at least one discovery of a concealed porphyry copper deposit in the Southwest. EM use has not been popular, in general, because of the many common sources of response which make recognition of porphyry anomalies difficult, and because of the limited depth of penetration.

Gravity is not used in identifying locales of potential porphyry copper deposits per se; normal geologic conditions are too complicated for this application. However, the gravity expression of one particular porphyry copper deposit was used successfully to guide the selection of sites for developmental drill holes. Dense skarn minerals having associated primary copper sulfides produced gravity highs which were prime targets of early drilling.

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(This is the classic deposit-modeling paper although Lowell does not like the term "model" and never uses it.)

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(If H. H. Read was correct when he said "the best geologist is the one who has seen the most rocks" then Silitoe is probably the best of the porphyry copper geologists. He has seen and written about more deposits, in more of the world, than anyone else.)

PRELIMINARY MODEL OUTLINE FOR FLUORINE-DEFICIENT PORPHYRY
MOLYBDENUM DEPOSITS

By
Ted G. Theodore

- I. Name of deposit type: F-deficient porphyry molybdenum deposit.
Includes most of the obviously subduction-related porphyry molybdenum deposits as classified by Sillitoe (1980). This tentative deposit-type is partly correlative with the granodiorite molybdenum systems of Mutschler and others (1981), the quartz monzonite type of White and others (1981), and the zoned porphyry molybdenum deposits of Woodcock and Hollister (1978). The deposit type proposed herein also corresponds with the low-fluorine, calc-alkaline molybdenum stockwork deposits of Westra and Keith (1981), and the porphyry deposits of a Mo-Cu association in the Russian literature. Several of the systems in the United States studied in detail thus far show zoned alteration patterns and sulfide ratios remarkably similar to porphyry copper deposits. However, in marked contrast to the average porphyry copper system, the typical fluorine-deficient porphyry molybdenum system shows an overall Mo to Cu ratio that is greater than one.

A possible, highly simplified overall classification of porphyry molybdenum systems may be:

F-deficient systems	Mostly continental
Transitional F-bearing systems	margin-related
F-rich, Climax-type systems	Continental margin related(?) and in rifted craton

In recent years, however, a relatively large number of Climax-type deposits and prospects have been discovered in the Basin and Range. These include Mt. Hope (classified as a transitional deposit by Westra and Keith (1981)), Spruce Mountain, McDermitt, and Majuba Hill all in Nevada, and Pine Grove, Utah.

- II. The model is extrapolated from studies primarily based on the Buckingham, Nevada, porphyry molybdenum deposit in the Battle Mountain mining district.
- III. Other deposits and(or) major prospects considered generally to be similar genetically to the type model are: Hall, Nev.; Pine Nut, Nev; Thompson Creek, Idaho; White Cloud, Idaho; Mount Tolman, Washington; Mike, Alaska; Burroughs Bay, Alaska; Quartz Hill, Alaska; and numerous other deposits in British Columbia; Shakhatawa, Obkoronda, Zhireken, Shtokverkovoye, Sarygichi, Paragachai, and Davenda and many others in the U.S.S.R..
- IV. Attributes
- A. Tectonic/stratigraphic
1. Magmatic arcs that, south of the Aleutian chain, are pre-Columbia River Basalt in age and that generally parallel the tectonic grain of the Mesozoic batholiths in the western Cordillera orogen.

2. The systems are spread widely throughout the geologic provinces of the Cordillera and rocks of any age may host the systems. In Canada and southeastern Alaska, from west to east, they may be localized in (1) isolated, transform-related(?) or possible regional extension-related (Hudson and others, 1981) mid-Tertiary alkali granite masses (Quartz Hill) that were emplaced into the Mesozoic-Tertiary Coast Range Plutonic Complex (CRPC) as defined by Brew and Morrell (1980), (2) early Tertiary granitic stocks and plugs in and associated with the CRPC itself, but mostly occurring in the east-adjointing Mesozoic Intermountain Belt, and (3) accretion-related early Cretaceous intrusions (Endako, Boss Mountain) in the Intermontane Belt. This belt hosts the bulk of the economically significant deposits in British Columbia. In the United States, rocks of the Idaho and Pioneer batholiths intrude the Omineca Crystalline Belt, and several molybdenum deposits (Thompson Creek, White Cloud) and numerous prospects occur near these batholiths' eastern margins. In the Basin and Range province, several late Cretaceous deposits (Buckingham, Hall, Pine Nut) and many prospects are related to small granitic bodies satellitic to the Sierra Nevada batholith. Thus, in Western North America the F-deficient porphyry molybdenum systems now known are confined largely to terrains containing Mesozoic and Tertiary intrusive rocks. This relation probably reflects the near-surface environment of such systems. The F-deficient porphyry molybdenum systems occur mostly within the North American porphyry copper-molybdenum belt, although some also occur well within the craton there they probably reflect the easternmost position of Cordilleran, possibly subduction-related magmatic arcs (Bookstrom and White, 1981).
3. Composite intrusions penecontemporaneous with molybdenum mineralization may be controlled locally by their emplacement along earlier structures, including either "high-level" or deep-seated ones. Many deposits show some control by structures at high angles to the regional Cordilleran tectonic trends.
4. The bulk of the significant mineralization is controlled by the overall extent of the associated igneous rock, either tightly in deposits wherein the wallrock consists of relatively impervious schists and gneisses (Quartz Hill), or "loosely" as in deposits hosted by quartz arenite and(or) arkose (Buckingham), or skarn (White Cloud).

B. Physical/chemical setting

1. Wall rock at the Buckingham deposit consists of Upper Cambrian Harmony Formation and a suite of small I-type, upper Cretaceous calc-alkaline intrusive rocks (avg SiO_2 about 68 percent). The magma series associated genetically with the F-deficient molybdenite systems typically shows a K_2O value at 57.5 percent SiO_2 that is less than 2.5, and the Peacock alkali-lime index is in the range 56 to 62 (calc-alkalic) (Westra and Keith, 1981). However, some deposits (Quartz Hill, for example) are associated with felsic granite (Hudson, Smith, and Elliott, 1979). In addition, some significant prospects recently have been recognized to be related to Cretaceous two-mica granodiorite

(Miller and Theodore, 1982). As with most porphyry deposits, the igneous rocks at the Buckingham deposit associated with mineralization include conspicuous quartz phenocrysts set in a well-developed, microgranular quartz-potassium feldspar groundmass. The rocks are altered sericitically, and in thin section show relict potassic assemblages (mostly secondary potassium feldspar). There are some extremely small breccia pipes and minor intermineral aplite at the Buckingham deposit.

2. and 3. At the Buckingham deposit, an early and widespread largely thermal metamorphism converted wide expanses of arenite to biotite hornfels, which extends in places far beyond the outer limit of flooding by silica in the quartz stockworks (Blake and others, 1978). Metasomatism associated with mineralization was superposed on the thermally metamorphosed rocks. In the deeper portions of the system, the overall zonal alteration toward ore is biotite hornfels--quartz stockworks showing potassic + sericitic assemblages--intense flooding by potassium feldspar very close to the mineralized intrusive rocks. The mapped outer limit of intensely developed quartz stockworks outlines and includes the surface projection of all ore. Abundant, closely spaced quartz veinlets throughout large volumes of rocks are one of the diagnostic indicators of this deposit type. Extremely fine grained molybdenite (the hexagonal poly-type characteristic of many porphyry molybdenite deposits) shows a prolonged paragenesis in the evolving system; it was deposited early with potassium feldspar along the selvages of the veins, it was deposited with white mica, and finally it also can occur together with carbonate along the veins' central parts. The overall sulfide content of the system is probably no more than 3 volume percent (mostly pyrite). Pyrite shows increased abundances at the top of the system where pyrite to quartz ratios in the stockwork veins typically are 1:1. In addition, the zone of stockwork veins is fringed by fractures filled by pyrite. There are locally some traces of bismuthinite and stibnite. Overall the system, more than 90 percent of the gangue is quartz. Although the content of copper (chalcopyrite) is extremely low in the molybdenite-rich cores of the system, such systems can contain economic ore bodies of both primary copper and secondarily-enriched copper. At Buckingham during its final hypogene stages in the Cretaceous, a copper-rich skarn slid off the upper portions of the system along a low-angle glide surface. This skarn yielded the bulk of the supergene copper in the Copper Basin porphyry ore body at the east end of the molybdenum system. Sporadic occurrences of galena, arsenopyrite, sphalerite, gold, and silver peripheral to the system may be related partly to subsequent Tertiary mineralization that is controlled mostly by structures.
4. The primary and pseudosecondary fluid inclusion signature of the deep portions these deposits is diagnostic, and distinct from the fluid-inclusion signature of the Climax-type deposit. The quartz stockworks contain very abundant, relatively large-sized fluid inclusions that are moderately saline (possibly 4 to 12 weight percent NaCl equivalent) and that homogenize mostly at moderate temperatures (250 -350°C). These fluid inclusions are

hosted by hydrothermal quartz in the stockwork veins and also by primary quartz phenocrysts in the intrusive rocks. Many deposits (Buckingham, Thompson Creek, Quartz Hill) contain significant but varying amounts of carbon dioxide (probably in the 4-8 mole percent range). NaCl and KCl daughter minerals are conspicuously absent, although some trapped(?) sulfides (including chalcopyrite) and iron oxide(s) have been identified. There is some evidence at one of the deposits (Buckingham) that the present level of erosion over the Mo-rich core may be just barely at the interface between the nonboiling and boiling regimes. At several other similar F-deficient molybdenum systems, the fluid-inclusion relations suggest that the associated fluids were not boiling thereby indicating the deep-seated environments of many of these systems.

5. The original character of ore and wall rock is generally well-preserved, but the system has been disrupted significantly by faulting that is both contemporaneous with mineralization and post-mineralization. Relations are complicated further by strong argillic and sericitic alteration associated with some of the supergene copper-rich zones in the upper portion of the system now marginal to the molybdenum core.
6. The depositional environment suggested is cooling of near neutral, mostly late magmatic fluids that may have incorporated a minor meteoric component sometime during the system's early stages. Related changes in pH of the fluid(s) may also have been important during the Mo-depositional stage(s) of the system.
7. The best geochemical signature for the Buckingham system is the content of Mo throughout the exposed stockworks. Mo contents are typically 70 to 300 ppm within the stockworks in contrast to 4 ppm Mo in the surrounding rocks. W is somewhat anomalous (20-40 ppm) within the veined intrusive rocks, but compared with the Climax-type moly deposits, the low concentrations of F at Buckingham (and all the other comparable deposits) is most striking. Most analyses of Mo-rich rock show F contents in the range 0.03 to 0.08 weight percent. At Buckingham, some epigenetic movement of Mo also occurred along some fractures and faults that were remobilized by the emplacement of post-Mo, middle Tertiary rhyolite, quartz latite, and granite. In places, this mineralization resulted in very high local concentrations of Ag, Au, Pb, Zn, and As. Soil geochemistry apparently is not as reliable as rock geochemistry for outlining the subjacent ore at Buckingham. Other Mo prospects in the Pioneer batholith, Montana, however, show anomalous concentrations of Ag, Mo, As, and Zn in soil samples that correlate quite well with altered rocks there (Pearson and Berger, 1980).
8. Isotopic signatures. Molybdenites from two of the late Cretaceous deposits (Buckingham and Thompson Creek) show ^{34}S values from +5 per mil to +11 per mil (see Hall and Schmidt, 1982). At the Buckingham deposit, $^{18}\text{O}/^{16}\text{O}$ and D/H isotopic ratios calculated for waters in isotopic equilibrium with the quartz stockwork veins, cluster near the base of the "magmatic waters box," suggesting some involvement of meteoric fluids very

early in the evolution of the system. Isotopically, there is no difference between veins showing potassium feldspar selvages and those showing white mica selvages.

- C. The presently known overall age span for this model type in the Cordillera is from about 140 m.y. (Endako) to possibly as young as 5 to 10 m.y. along the Aleutians. Many of the deposits associated with granitic bodies satellitic to the east of the main masses of the Idaho and Sierra Nevada batholiths are late Cretaceous in age. Wallrocks hosting the deposits include rocks as old as Upper Cambrian.
- D. The Buckingham deposit shows no distinctive aeromagnetic signatures; it occurs in a plateau of gamma values just south of east-west-trending contours of slightly higher magnetic intensity. These contours parallel the surface outcrop of the Mo-mineralized intrusive rocks. The White Cloud and Thompson Creek deposits are on the flanks of well-developed aeromagnetic highs, but rocks from the deposits themselves show extremely low magnetic susceptibilities reflecting the intense destruction of primary magnetite.
- E. The overall content of molybdenum in ore shows a fairly uniform, although locally complexly shaped (Buckingham), distribution through relatively large volumes of rock. The ores are either bounded rather sharply with their noneconomic wallrocks (Quartz Hill), or the ores show a marginal, gradual decrease in the content of Mo and a concomitant increase in the content of Cu (Buckingham).
- F. A grade/tonnage model, updated from Singer and others (1980), of fluorine-deficient porphyry molybdenum systems reveals that both tonnage and grade follow log-normal distributions and are statistically independent, based on data from 20 such deposits (Theodore and Menzie, 1982). The median tonnage of the deposits is 38 million tons; 10 percent of the deposits may be larger than 490 million tons. The median grade of these deposits is 0.10 weight percent Mo; and 10 percent of the deposits may have grades larger than 0.17 weight percent Mo. Almost all economically significant deposits of the F-deficient-type porphyry molybdenum deposits, however, show overall grades lower than the Climax-type porphyry molybdenum deposits.
- G. Products from the Battle Mountain district include: Cu, Au, Ag, Pb, and Sb. Some deposits will show no byproducts, others may show Cu, Ag, and possibly W. As such, byproducts from this general class of molybdenum deposit will be quite varied.

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GRANITE MOLYBDENITE SYSTEMS

By
Steve Ludington

The Deposit Type Is: GRANITE MOLYBDENITE SYSTEMS

Specific Deposit Modelled Is: HENDERSON, COLORADO

Other Similar Deposits And Prospects:

Deposits - CLIMAX, CO

MT. EMMONS, CO

QUESTA, NM (includes Sulfur Gulch, Goat Hill, and Log Cabin
deposits)

Prospects - CHICAGO BASIN

HAHNS PEAK

TREASURE MTN. DOME

REDWELL BASIN

HORSESHOE BEND

LEAVENWORTH CREEK COLORADO

MOUNT ANTERO

WINFIELD

MIDDLE MTN.

TURQUOISE LAKE

BOSTON PEAK

CAVE PEAK TEXAS

MARYSVALE

PINE GROVE UTAH

SAND PASS

McDERMITT

MAJUBA HILL NEVADA

MT. HOPE

LITTLE FALLS

CUMO IDAHO

IMA

BALD BUTTE

BIG BEN MONTANA

EMIGRANT GULCH

ATTRIBUTES Introduction

Large, 'low-grade' molybdenite deposits seem, on the basis of chemistry of the source plutons, age, and tectonic environment, to fall into two classes, here termed "Granite" and "Granodiorite" Molybdenite Systems. This model deals only with the former.

All these deposits are closely associated and/or derived from plutons which are granite in the sense of Tuttle and Bowen, i.e., normative $OR+AB+Q > 80\%$, and when $OR+AB+Q$ is normalized to 100%, $AB \geq 20\%$, $OR \geq 20\%$, and $Q \geq 20\%$.

All these deposits are emplaced within a few km of the earth's surface, and are, in a sense, subvolcanic, whether volcanic rocks are now present or not.

Tectonic Setting

Continental scale.--Granite molybdenite deposits seem to be associated in time with the transition between compressive and extensional tectonic regimes, i.e., to occur early in the plutonic cycle characterized by the continental basalt-rhyolite association. They are almost all far from continental margins (Quartz Hill, AK?).

Local scale.--Often said to be found at the intersection of lineaments--I find this of dubious value. In Colorado and New Mexico, there are a series of deposits and prospects aligned more or less along the Rio Grande Rift. Pine Grove is on an E-W 'Mineral Belt'.

Structural control.--Largely insignificant, except as a control of emplacement of the source pluton; ore tends to be concentric about the source pluton. An important exception is at Questa, where proximity to the topographic and structural walls of a caldera has resulted in local structural control.

Physical/Chemical Setting

Wall rock.--Composition might affect mineralogy of ore, but known deposits are largely in granitic hosts, with some quartzite. A carbonate host would be interesting, but is unknown to me. More important is that the porosity and permeability of the host rock should probably be low, lest the fluids, being noncirculating, will escape, and the mineralization will be diffuse and low grade.

Source rock.--Because these deposits are thought to be derived directly from granite magmas, the composition of the source plutons is of interest. All have normative OR+AB+Q $\leq 80\%$, and $\text{SiO}_2 \geq 74\%$. Other favorable characteristics are thought to be:

F	$>0.1\%$ (but depends on modal mineralogy)		
Rb	>250 ppm	Ba	<300 ppm
Sr	<50 ppm	Sn	≥ 5 ppm
Cs	>10 ppm	U	>10 ppm
Nb	>50 ppm	La	≤ 50 ppm
Ta	>10 ppm	Y	≥ 50 ppm (Questa an important exception)

(These numbers are not precise, nor is the list of elements complete, but should convey the general idea.)

Alteration -

Zonal pattern: Symmetric to ore; Kfspr \rightarrow qtz-sericite-pyrite \rightarrow propylitic; sequence is a matter of debate. Most alteration is probably contemporaneous.

Mineralogy: Similar to classic zonal minerals of porphyry Cu deposits, but topaz may be important in inner zones, and fluorite is nearly ubiquitous throughout. Mn-rich (also F-bearing!) garnets may be found as alteration minerals. Fluorine content of micas may be a useful tool.

Texture: Largely pervasive alteration--vein selvages are restricted largely to later (retrograde?) effects.

Ore mineralogy -

Minerals: Quartz-molybdenite-fluorite+K-feldspar veins in a K-feldspar-quartz metasomatite.

Textures: Stockwork of 0.1 to 5-cm veinlets.

Zonal pattern and sequence: Ore veinlets are remarkably uniform in composition and texture. Falloff in grade at edge of ore bodies is largely due to fewer veins, not less Mo in veins. Any one mineralization event seems to consist of contemporaneous vein fillings.

Mineral chemistry: Ore and gangue minerals are believed to be end-members; molybdenite is low in rhenium.

Fluid inclusions -

There exist no exhaustive studies. I believe all deposits will contain primary brine inclusions with >500°C filling temperatures. Many cooler, more dilute, later fluids have, of course also been trapped, obscuring the primary record.

Degree of preservation of original character is nearly complete in all known cases.

Multiple intrusion/mineralization is nearly ubiquitous, and may be superimposed.

Interpreted chemical environment -

The ore fluid, just before deposition, is interpreted to be (1) almost entirely derived from granite magma, (2) hot (500°C), (3) a saline, alkali fluosilicate melt, perhaps H₂O-33, K, NaF-33, Si-33 MoS₂-1, +Fe, Al, Ca.

(This part is highly speculative!)

Geochemical signature -

Elements in the primary dispersion halo may include F, Li, Be, Sn, W, Rb, Cs(?), Mn, Pb, Zn. The most widespread are probably F and Li, but the work hasn't been done publicly.

For stream sediments, the most useful elements are probably F, Sn, Nb, Ta, W, and Mo, if mineralization is exposed.

If the ore is not unearthed, a useful approach is to search for the geochemical signature of associated intrusives with similar character. If the ore is exposed to erosion, F and Mo should suffice.

Important mediums are stream sediments, heavy-mineral concentrates, probably water, and rock geochemistry.

Isotopic signature -

The intrusions apparently have rather low initial Sr ratios. Light stable isotope work is almost nonexistent as yet.

Age

All granite molybdenite deposits in the Western United States are younger than 50 m.y., and show a general younging to the south, perhaps corresponding to the cessation of active subduction. It is not clear that deposits corresponding closely to these are found on any other continent, or of any other age.

Geophysical Signature

Gravity.--The source plutons may be expressed as a gravity low, depending on the density of the host rock. Where information is sufficient, they seem to lie atop and along the margins of large, buried granitic batholiths which may be revealed by regional gravity data.

Induced polarization.--Ore (MoS_2) and/or the quartz-sericite-pyrite alteration zone may be found by IP. Magnetics.--Air mag may show a low due to extensive magnetite- destructive alteration, but may have a high due to magnetite alteration zones--depends on depth of burial.

Geophysics has not been instrumental in discovery of any prospect or deposit that I know of.

Ore Grades and Distribution

For underground mining, ore is about +0.25% MoS_2 , for surface mining, about +0.10%. (As of March, 1982, these numbers are somewhat higher, due to the recent decline in price.)

Ore bodies tend to be compact saucers ($<1 \text{ km}^2$) with abrupt walls at about 0.1%--high-grade regions may surpass 1%, but $0.5 \pm 0.2\%$ is most common.

Tonnage

Most deposits and prospects contain between 100 and 500 million tons of ore. Smaller, lower grade deposits are known, but not quantified. Not enough deposits are well-known to approach this problem on a statistical basis.

Products and Byproducts

The primary product at all deposits is molybdenum. Tin and tungsten may be produced in small quantities. Uranium may occur in sufficient quantities to make recovery possible. Copper is significant in its near-total absence.

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CHARACTERISTICS OF THE COLORADO-TYPE (CLIMAX-TYPE) MOLYBDENUM DEPOSITS
READILY RECOGNIZED AT THE SURFACE

By

Paul K. Theobald, Jr.

1. Geologic

A. Siliceous igneous activity

- i) Porphyritic near the deposits and most easily characterized by glassy, sometimes smoky, bipyramidal quartz phenocrysts.
- ii) Aphanitic rocks more remote from the deposits (up to several kilometers) are often difficult to recognize as igneous rocks.
- iii) Complex igneous history. Though there is evidence that several intrusive events are required to produce a commercial deposit (today's market), the complexity of the intrusive system is usually not understood until late in the exploration effort (often well after the discovery).
- iv) Confined cupolas. There is evidence that igneous pulses that vent lose their competence to produce a deposit. The presence of an extrusive phase should not be taken as negative evidence, however, because individual pulses may vent while others produce a deposit (Urad and Henderson) or the confined cupolas may invade older volcanics (Questa).

B. Complex structural intersections serve to localize the repeated invasion of intrusives to a high level in the crust.

C. Mid-Tertiary age of the igneous complex is a favorable criteria in the central Rockies because this is the age of siliceous volcanism in this province. This criteria probably does not apply elsewhere.

2. Geophysical

A. Gravity lows of moderate to large intensity but small areal extent reflect both the siliceous rocks and the alteration around mineralized cupolas. In the central Rockies these are generally distributed around the edge of a regional gravity low presumed to reflect a parent mass of batholithic proportions.

B. Remote sensing has not been used, to my knowledge, in the classical sense, but one of the most characteristic surface features is the striking color variation due to abundant black manganese oxides, strong yellow, lead-stabilized jarosite, and bright-red (lepidochrosite at Henderson and akaganeite at Questa) iron oxides against a background of bleached rock. There is a common association of molybdenum deposits with Red Mountains.

3. Pervasive alteration

A. Silicification near the deposits.

B. Leaching in an argillic or phyllic zone in a halo a kilometer or so in diameter. This is the zone of strong color anomalies.

C. Chlorite is diagnostic of a propylitic halo several kilometers in diameter.

4. Geochemical

A. Molybdenum when the deposit is exposed (perhaps more remotely in arid environments where molybdenum is more mobile).

B. Tin (cassiterite) and tungsten (usually huebnerite) just above the deposit. As these are refractory minerals, only mechanical dispersion is important and the tin-tungsten zone must be exposed to be detected.

- C. Zinc and lead in a halo generally a kilometer or more from the deposit.
- D. Low-level silver enrichment in a wide halo generally outside of the zinc halo.
- E. Fluorine in a pervasive, pipelike anomaly a kilometer or so in diameter extending upward from the deposit and in structurally controlled anomalies extending laterally from the deposit for many kilometers. Several fluorine-rich minerals contribute to the central anomaly, but fluorite is the most common in peripheral anomalies. Though easily recognized purple fluorite is often present, easily overlooked colorless or pale blue to green fluorite is more characteristic of the molybdenum deposits.
- F. Copper is abnormally low with these deposits and its absence may serve to separate the pure molybdenum system from similar base-metal systems which are usually rich in copper.

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MODEL FOR CONTACT METASOMATIC TUNGSTEN/COPPER/GOLD DEPOSITS

By

James E. Elliott

Introduction

Contact metasomatic deposits are common in the Idaho-Montana region and have been important producers of copper, gold, and tungsten as well as minor quantities of other metals. In terms of future mineral resource potential, this type of deposit is relatively more important for tungsten than for gold or copper. Examples of this type of deposit are the Cable gold mine near Georgetown Lake, the Spring Hill gold deposit near Helena, the Calvert Hill and Brown's Lake tungsten deposits in the Pioneer Range northwest of Dillon, and the Mackay and Seven Devils copper-producing districts of Idaho.

By definition this type of deposit involves a contact zone between an intrusive and a reactive host rock; a sedimentary carbonate in nearly all cases. Other names for this type of deposit are skarn and tectite.

Regional Setting

Contact metasomatic deposits form in a plutonic environment, spatially related to batholiths. In the western United States these intrusives are predominantly calc-alkaline, usually granodiorite or monzogranite (quartz monzonite in older terminology). These deposits are found at borders of batholiths, in contact zones of satellitic plutons or in roof pendants in plutons.

These plutonic regimes indicate active tectonism and orogeny. In western Montana the plutonic rocks were emplaced during waning phases or after major thrusting. Host rocks for contact metasomatic deposits are typically miogeosynclinal or shelf facies carbonate rocks. The more pure calcite limestones and marbles are the most favorable hosts, but the presence of interlayered impure carbonate rocks and siliceous clastic rocks may enhance the favorability of certain stratigraphic sequences.

District/Deposit Characteristics

The intrusives which are associated with contact metasomatic deposits are commonly the latest of a series of intrusives. They are usually equigranular, porphyritic texture is less common, and are biotite or biotite-hornblende-bearing granitoids. Relative to associated intrusives the metallogenic intrusive is usually more leucocratic and quartz-rich. Late dikes and quartz veining are common.

In Idaho and Montana the most favorable hosts for tectites are the middle and upper Paleozoic carbonate sedimentary rocks. Selective replacement and metasomatism is probably the greatest for the purer carbonates and the occurrence of thinly bedded pure carbonate that is interbedded with impure carbonates and siliceous clastic rocks is probably the most favorable environment for two reasons: (1) During folding and/or faulting there is a greater tendency to develop fracture zones of high permeability in these sequences. Thick-bedded pure carbonates tend to deform plastically without developing zones of high permeability. High permeability is essential in

providing access of metasomatic fluids to reactive carbonate beds. (2) Impure carbonate and siliceous clastic beds also provide a nearby source for silica, alumina and other materials for the formation of calc-silicate minerals of the tactite zone.

Alteration effects associated with tactite zones are usually most evident in the carbonate rocks bordering the tactite. Alteration of the intrusive, if present, is usually restricted to a very narrow zone at the contact. Tactite zones are commonly zoned reflecting decreasing thermal and metasomatic effects away from the contact. Alteration in carbonate rocks adjacent to the tactite include bleaching (probably due to removal of organic carbon), recrystallization to marble and the development of minor amounts of calc-silicate minerals such as scapolite, idocrase, or tremolite. Alteration and replacement can be very complex and varied due to rapid changes in pressure, temperature, and composition of the fluids. Equilibrium is seldom reached and these zones commonly develop in several stages of isochemical and allochemical metamorphism. Some commonly observed replacement features indicative of more than one stage are: late iron-rich dark-brown andradite garnet as replacement of early iron-poor light-colored grossular garnet, replacement of early calc-silicate minerals by sulfides, replacement of early high-temperature pyroxene by lower temperature amphibole and/or epidote.

Structure is a very important control on the formation of contact metasomatic deposits. The structure of the host rocks, the dip of bedding relative to the intrusive contact, jointing/fracturing of the intrusive and the configuration of the intrusive contact are important ore controls. Folds and faults in the host rocks and joints and fractures in the intrusive provide permeable channels for movement of metasomatic fluids. Most favorable situations are where the intrusive intersects the limb of an anticline of favorable host rocks or a fold in the host rocks plunges steeply towards the intrusive contact. Bedding dipping towards the intrusive contact is more favorable than bedding parallel to or dipping away from the contact because the chances for fluids migrating up along the intrusive contact to come in contact with favorable beds are increased. The configuration of the intrusive contact may affect the localization of deposits in one of several ways. Troughs in the contact may aid in channeling metasomatic fluids to a reactive host rock. Overhangs of the contact may cause "ponding" of fluids and thus promote reaction. A shallowly dipping or flat contact is judged more favorable than a steeply dipping one because the flatter contact promotes increased thermal effects on the host rock and impedes the movement of metasomatic fluids moving outward from the intrusive or up along the contact.

Contact metasomatic deposits occur in many forms but they are usually irregular or podlike. They may be stratiform where controlled by the original bedding in the host rocks. Contacts are more commonly fairly sharp rather than gradational between ore and waste.

The bulk geochemistry of these deposits is quite similar from one deposit to another but there is an apparent difference between gold/copper deposits and tungsten deposits. This is due to the greater abundance of sulfides and chalcophile elements in gold/copper deposits in the first case and the greater abundance of lithophile elements with tungsten deposits in the latter case. The trace-element suite for gold and copper deposits is quite similar including silver, zinc, lead, and arsenic along with gold and copper. In

addition, bismuth and molybdenum occur commonly with copper deposits. For tungsten deposits, the trace-element suite includes molybdenum, copper, bismuth, beryllium, tin, fluorine, and niobium together with tungsten.

Contact metasomatic copper and gold deposits commonly are oxidized and occasionally show evidence of supergene enrichment. Both oxidized and enriched zones yield higher grades of ore than the primary ore. Supergene enrichment is not an important factor in tungsten deposits of this type.

Mine/Outcrop/Drill-hole Characteristics

The mineralogy of contact metasomatic deposits is relatively simple for the ore minerals, but is usually complex and diverse for gangue minerals. In copper deposits the ore mineral is predominantly chalcopyrite but bornite is sometimes present. In gold deposits, gold occurs in the native state as disseminated grains and as inclusions in pyrite and arsenopyrite. Scheelite is the ore mineral in tungsten-bearing tactites.

Gangue minerals include silicates, oxides, carbonates, sulfides, and miscellaneous species. Garnets of the grossular-andradite series, pyroxene of the diopside-hedenbergite series, amphiboles of the tremolite-actinolite series, quartz and epidote are the most prevalent silicates. Other nonopaque minerals include calcite, green hornblende, wollastonite, idocrase, biotite, fluorite, scapolite, olivine, and spinel. Common opaque minerals are magnetite, hematite, pyrite, pyrrhotite, arsenopyrite, bismuthinite, and molybdenite. In the oxidized zone a variety of species may occur. Common are limonite, iron-rich clay minerals, malachite, azurite, chrysocolla, black copper-oxides, and cerussite.

Tactites are usually zoned and show evidence, in commonly observed replacement textures, of having formed in several stages of metasomatism. Mineral zoning and banding may mimic structures and stratification in the preexisting sedimentary rock. Fractures may be either pre- or post-ore. Veins are uncommon and may be limited to late barren quartz and calcite veins. Vein relationships in intrusive or at contact may provide valuable information on genesis of deposits. Petrographic studies of some tactite zones reveal much evidence of disequilibrium. Paragenesis and multi-stage history can usually be deciphered from replacement and overgrowth textures in minerals.

Zoning is usually related to the intrusive contact and may extend into the intrusive (endocontact or endoskarn) as well as into the host rock (exocontact or exoskarn). The mineralogical zonation is the result of decreasing metasomatism and thermal effects away from the contact into the host rock. Compositional differences in the host rock and that of the intrusive will also control zonation. The details of zoning may be very complex and related to features such as fractures, configuration of the contact and structure of the host rock which control the movement of metasomatic fluids.

The highest grade zones, in terms of temperature and degree of metasomatic change, usually at or close to the intrusive contact, commonly consist of iron-rich garnet and pyroxene, an anhydrous assemblage. Lower grade zones show a greater abundance of hydroxyl-bearing species such as amphibole and epidote. Different degrees of metasomatism are commonly reflected in the iron:calcium ratios in these minerals. The outermost zones have idocrase, scapolite, wollastonite, iron-poor garnet, tremolite and may be principally the result of isochemical metamorphism.

In form, tactites are usually quite irregular and variable even within individual mines. They are usually podlike and conformable with the intrusive contact. They may be stratiform and continuous for several tens of meters away from the contact, following bedding of the host rock.

Tactites are the result of profound changes in bulk chemistry of the host rock. Metasomatism results in the addition of large amounts of SiO_2 , Fe, Al_2O_3 , and Mn. The total gain may be on the order of 50 to 60 percent by weight. The principal losses are in CaO and CO_2 .

Genesis

Contact metasomatic deposits are the result of hydrothermal solutions emanating from a crystallizing granitic magma and reacting with a favorable host rock at high temperatures and pressures. By the modified Lindgren scheme these are classed as hypothermal-2; suggested conditions are temperatures of 300-600°C, pressures of 800-4,000 atms and depths of 10,000 to 50,000 feet.

Ages of mineralization of host rocks and source rocks for these deposits are variable but the most common mode in the western United States is mineralization of late Mesozoic age where Paleozoic host rocks are intruded by late Mesozoic granitic plutons.

Stable isotope studies of contact metasomatic deposits are very few. One study of skarns in the Osgood Mountains, Nevada, by Taylor and O'Neil (1977) indicates that water in metasomatic fluids was derived primarily from magmatic sources during the early stages, and meteoric water was involved in later stages. Sulfur and carbon were derived from magmatic sources.

Temperatures, based on fluid inclusion studies, are in the range 300-600°C at pressures of 0.5 to 2 kilobars. Studies of individual deposits indicate the composition of the metasomatic fluids and the mineralogy of the resulting tactites is controlled by the partial pressures (or fugacities) of CO_2 , O_2 , S_2 , and F_2 . Predicted values are in the following ranges:

$f(\text{CO}_2)$ - $10^{-0.7}$	to	$10^{-1.5}$
$f(\text{O}_2)$ - 10^{-20}	to	10^{-40}
$f(\text{S}_2)$ - 10^{-5}	to	10^{-10}
$f(\text{F}_2)$ - 10^{-30}	to	10^{-40}

The geologic environment in which these deposits are formed is where granitic batholiths are emplaced into miogeosynclinal carbonate facies rocks. The deposits are formed at contacts of mesozonal to epizonal plutons on the fringes of these batholiths at high temperatures and pressures.

Prospecting Techniques

Geophysical techniques which are useful for the location of contact metasomatic deposits include magnetic, gravity and electrical methods. Regional aeromagnetic surveys are useful in location of buried plutons, usually appearing as magnetic highs, in regions where favorable carbonate rocks are known to exist. Once a target has been selected, where intrusives are in contact with favorable host rocks, detailed gravity and magnetic studies along contact zones would be useful for detecting buried deposits. Typical tactite has a density of 3.0 to 3.5 compared to density of 2.6 to 2.7 for carbonate and granitic rocks. Many tactites are magnetic because of the presence of magnetite and/or pyrrhotite. Detailed electrical methods would be useful because most tactites contain sulfide minerals either as disseminations or in fairly massive zones with up to 50 percent sulfides.

Geochemical prospecting should be concentrated on contact zones where favorable host rocks are in contact with granitic intrusives. Drainage, soil and rock sampling should be considered and evaluated by orientation surveys. For gold/copper deposits the methods should be designed to test for anomalous amounts of silver, lead, zinc, bismuth, arsenic, fluorine, molybdenum, and tungsten as well as gold and copper. For tungsten deposits, the methods should test for anomalies in copper, molybdenum, bismuth, beryllium, tin, fluorine, and niobium in addition to tungsten.

Remote-sensing techniques would not prove to be particularly useful because the target size is very small. These techniques would be most useful in outlining contacts of plutons, distinguishing carbonate units and locating zones of bleaching in carbonate rocks in proximity to intrusives.

Economics

For gold and copper deposits the grade is generally high but extremely variable. For gold, grades of 1 to 2 oz/ton are common; for copper, grades of 5 to 20 percent are common. Minor amounts of silver, lead, and/or zinc may also occur. For tungsten, grades are generally lower and more uniform than for gold and copper. Tungsten deposits which have been or are being mined have grades of 0.35 to 1 percent WO_3 .

These deposits are usually relatively small, nearly all are less than one million tons; worldwide those in the class of 1 to 10 million tons are rare and those in excess of 10 million tons are less than 10.

For gold/copper deposits, silver, lead, and zinc are common byproducts, and for tungsten deposits copper and molybdenum may be byproducts. Potential byproducts would include bismuth and fluorite. Since many of these deposits are mined by open-pit methods, the same environmental factors would apply as with many open-pit mines of other deposit types.

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TIN GREISEN MODEL

By

Bruce L. Reed

Model: Tin greisen; massive and greisen veins; composite, based on several tin greisen deposits (Erzgebirge, Ardlethan, Herberton, Kazakstan, etc.), and may be representative of a "typical" tin greisen deposit.

Tectonic/Stratigraphic Setting

Continental.--Elongate foldbelt of thick platform sediments, + volcanic rocks deposited on stable cratonic shield. Generally, nonfoliated "intrusive" granitoids or their extrusive equivalents post-date major folding and belong to the last products of magmatic activity. (Anorogenic granitoids in ancient metamorphic cratonic terranes may have associated tin-bearing greisens and tin-bearing pegmatites, i.e., Rondonia, Black Hills, Central Africa; such primary tin ores are generally of minor importance.)

Local.--Granitoids, relatively high level (high plutonic to deep volcanic--2.5-4 km?), small multiphase stocklike bodies 3-10 km in diameter which may be connected to a composite batholith at depth. (External, shallow-depth plutons do not produce "typical" greisens.) Emplacement of granitoids may, in part, be controlled by major fracture-suture zones. Multiphase intrusion and mineralization are ubiquitous.

Structural.--Greisen lodes located in or near cusps (granite peaks or cupolas) and ridges developed on the roof or along margins of granitoids, also in faults and fractures, in part related to the intrusion of granitoids, developed during late- and post-consolidation stages of magma crystallization.

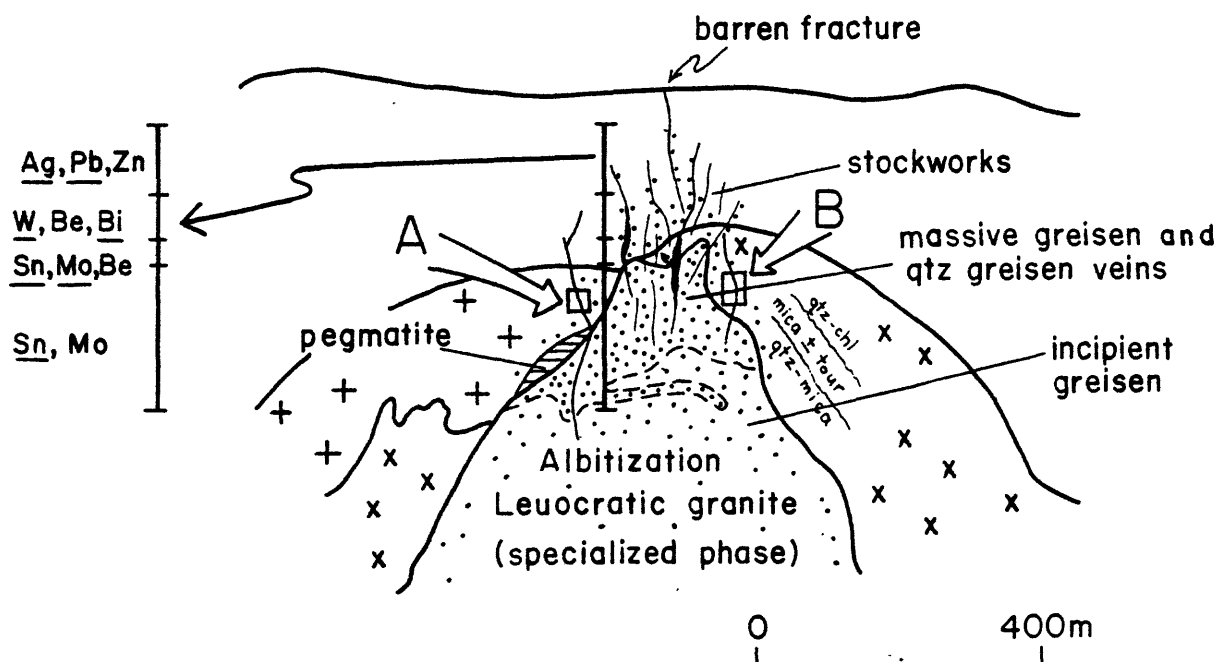
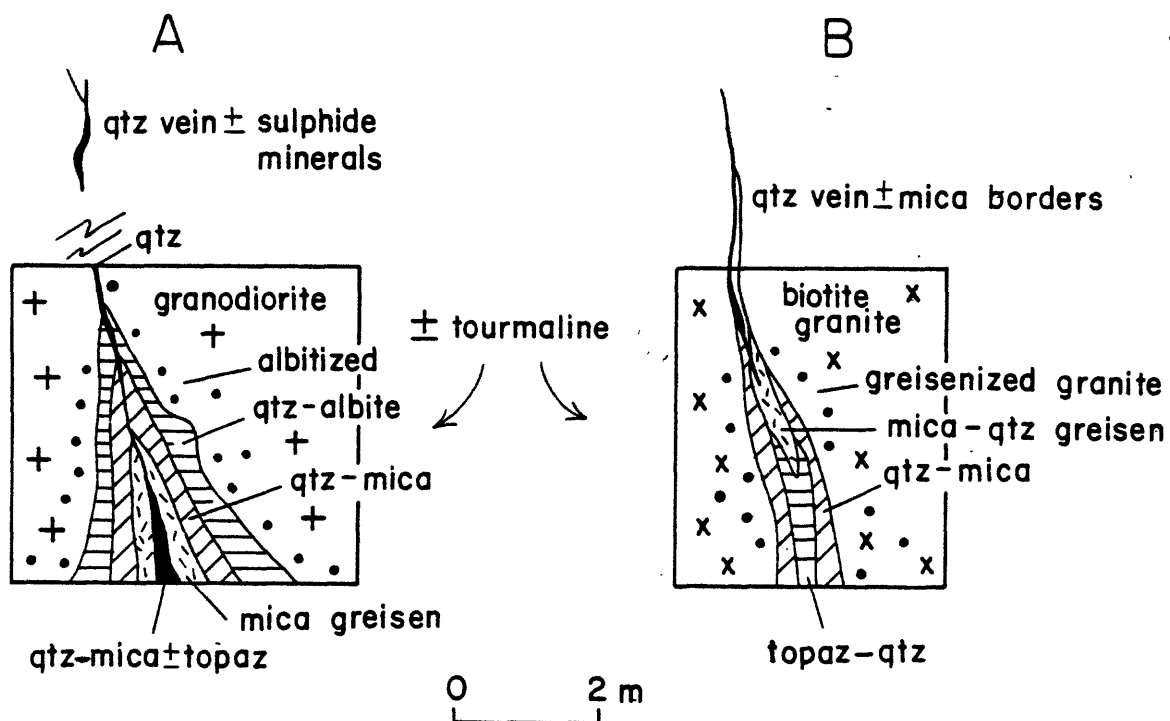
Mineralized structures are exceedingly varied, the most common being disseminated cassiterite in massive greisen, fissure veins and stockworks (either the upper parts of the cusp or in overlying wall rocks); less common are pipes, lenses, disseminations, and tectonic breccia.

Lithologic control.--Tin-bearing greisens are generally post-magmatic and associated with a late fractionated melt (leucogranite).

Physical/Chemical Setting

Wallrock.--Wall rock is variable, ranging from early precursor granites to whatever medium is being intruded. (Greisens can be formed in any wall rock environment, but typical assemblages are developed in an aluminosilicate environment.)

Alteration.--Extremely varied due to pulsation in supply of fluids and changes in solution composition, pH, temperature, etc. (Adherence to a specific model is considered unwise in the search for undiscovered deposits.) Inverse zoning common, due to low temperature or change in confining barriers.



PRECURSOR GRANITES

x x biotite granite

+ + hornblende-biotite granodiorite

Conceptual model for cassiterite-bearing massive greisen and greisen veins. Scales are approximate.

Pregreisenization (contact effects).--

Granite - albitized, hornfelsized
Shales, sandstones - hornfelsized
Limestone - marmorized
Mafic intrusive rocks - amphibolitized

Greisenization.--Incipient greisen (granites) - muscovite + chlorite, tourmaline, and fluorite.

Greisenized granites--Quartz, muscovite, topaz, fluorite, + tourmaline; original texture of granites retained; K-feldspar replaced in varying degrees by sericite, + topaz, quartz; albite and oligoclase slightly replaced by sericite; albitization - perthite becoming albite-rich, albite replaces K-feldspar; biotite - ragged crystals, sericite + chlorite; minor topaz and fluorite; cassiterite - generally rare (<500 ppm Sn).

Massive greisen (granite)--Texture and composition variable, typically no original texture preserved (with the possible exception of quartz phenocrysts). Essentially comprised of quartz-muscovite-topaz + fluorite and tourmaline. Tourmaline can be ubiquitous as disseminations, concentrated or diffuse clots, or late fracture fillings; cassiterite--variable (0.0X - 0.X% Sn).

Greisen veins--Pervasive massive greisen development may be accompanied by greisen veins that extend beyond main zone of greisenization. Alteration halos adjacent to tin-bearing greisen veins/veinlets (quartz + topaz with mica-rich borders) generally restricted, depending on proximity to source, range in width from a few millimeters to generally <4 meters. (Detection and interpretation of such veins is a priority in detection of tin-enriched cusps at depth--but greisen veins may not be present.) In some cases, enclosing granites are "reddened" (hematitization) several meters from a greisen vein system.

A typical vein in aluminosilicate rocks (sandstone, shale, granitoids and their extrusive equivalents) would consist of (towards the vein) sericite-quartz+chlorite, quartz-muscovite, quartz-muscovite-topaz, quartz-topaz. Tourmaline may be present throughout. Fluorite generally ubiquitous in carbonate terrane. Textures varied; mottled, banded, lepidoblastic; vugs near center of vein.

Ore mineralogy.--Generally zonal development of cassiterite + molybdenite, cassiterite + molybdenite + arsenopyrite + beryl, wolframite + beryl + arsenopyrite + bismuthinite, Cu-Pb-Zn sulfide minerals + sulphosalts, quartz veins, + fluorite, calcite, pyrite.

Cassiterite irregularly disseminated in lower parts of greisens becoming more abundant (frequently as quartz-cassiterite + molybdenite stockworks) toward roof.

Degree of preservation.--Absence of supergene enrichment. Superimposed multiphase alteration/mineralization progressively replaces earlier greisen phases; residual (eluvial or alluvial) cassiterite from exposed greisens present.

Geochemical environment/signature.--Most tin-greisen deposits are associated with calcalkaline biotite and/or muscovite granites which evolved through a normal pattern (i.e., towards more felsic differentiates). Precursor granitoids, an indication of heredity and a precondition of yet-to-come accumulation of tin in subsequent fractionated specialized granites, are (as compared to low calcium granites) generally enriched in Sn, Li, Rb, Be, F, U, Th, and Cs, and depleted in Ba, Sr, and Sc.

Highly evolved specialized granites may have high contents of SiO_2 (>73%) and K_2O (>4%), and are depleted in CaO , TiO_2 , MgO , and total FeO . Their differentiation index is generally >90. They show enrichment in Sn, F, Rb, Li, Be, W, Mo, Pb, B, Nb, Cs, U, Th, Hf, Ta, and most REE, and impoverishment in Ni, Cu, Cr, Co, V, Sn, Sc, Sr, La, and Ba. Suggested and imprecise values (perhaps influenced by personal observation rather than by a statistically significant world-wide compilation) for some of these elements are (in ppm): $\text{Sn}>20$, $\text{F}>3000$, $\text{Rb}>450$, $\text{Li}>300$, $\text{Be}>10$, $\text{B}>300(?)$, $\text{Pb}>50$, $\text{W}>5$, $\text{Mo}>3$, $\text{Ba}<100$, $\text{Cu}<3$, $\text{Sr}<20$, and $\text{La}<30$. These elements may be vertically zoned and best expressed in the apical zones of an intrusion.

Biotite is a notable concentrator of Sn, F, Rb, Li, etc., in specialized granites; significance uncertain, but may have released tin during secondary alterations by alkaline metasomatic solutions containing F and Cl and precipitated cassiterite when the pH of the solution dropped and temperature (300-550°C) decreased. (Field evidence for the importance of process is not proven.)

Important accessory minerals in specialized granites include topaz, fluorite, tourmaline, or beryl.

Granitoids associated with tin deposits are S-type and belong to the ilmenite series.

Late-stage leucogranites are favorable geochemical environments for tin deposits because tin is not incorporated into the main mineral constituents (quartz and feldspar) and therefore available to crystallize as cassiterite. Tin, however, may be present as isomorphous substitution in biotite and muscovite and available for later extraction.

Isotopic and REE signatures.--Lead isotopes may prove useful in evaluating terranes for their tin producing potential. The $^{207}\text{Pb}/^{204}\text{Pb}$ ratios from southeast Asia and Bolivia, two major tin belts of the world, are unusually high. Values range between 15.6 and 15.8 (Bruce Doe, written commun., 1982), even though these tin belts differ greatly in age and are half-a-world apart. Lead isotope data also suggest that the source of the lead in cassiterite-sulfide lodes is continental crust rather than oceanic.

Initial $^{87}\text{Sr}/^{86}\text{Sr}$ values for precursor and specialized granites also suggest a crustal source for the granitoids. Values are generally >.707 and may be as high as .720.

Total REE of specialized granite are generally higher than those of precursor granites, but the chondrite normalized trends are different. Precursor granites generally show a moderate negative europium anomaly, decreasing light rare earths, and a uniform, or slightly decreasing, heavy

rare earth pattern. Limited data indicate that specialized granites have a pronounced negative europium anomaly and lower concentrations of light rare earths as compared to their heavy rare earths.

Age

Major tin mineralization is reflected by periods of major crustal orogeny; ages range from Precambrian to Middle Tertiary. For some areas (Belitung, Cornwall, Transbaikal) the temporal relation between initial granitoid emplacement and greisenization is in the order of 20 m.y.

Although several ages of granites may occur within an orogenic belt, tin mineralization is generally temporally related to a specific period of granitoid emplacement (i.e., Erzgebirge-younger Permian complex, Main Range (Malaysia)-Triassic, Alaska/Yukon-Late Cretaceous). This is not the case for Bolivia (Upper Triassic and middle Tertiary) which may be due to subduction-related anatectic magmas periodically generated within a tin-enriched crust (derived from the Brazilian shield).

Geophysical Signature

Depending on characteristics of surrounding terrane, aeromagnetic anomalies can enable one to locate contact-metamorphosed rock (annular anomalies) or concealed granitic cusps. Mineralized cusps commonly form part of a composite intrusive sequence, and their presence might be difficult to identify. Magnetic, seismic, and gravimetric (small lows distributed over a regional gravity low) studies could possibly recognize concealed altered cusps.

Grade

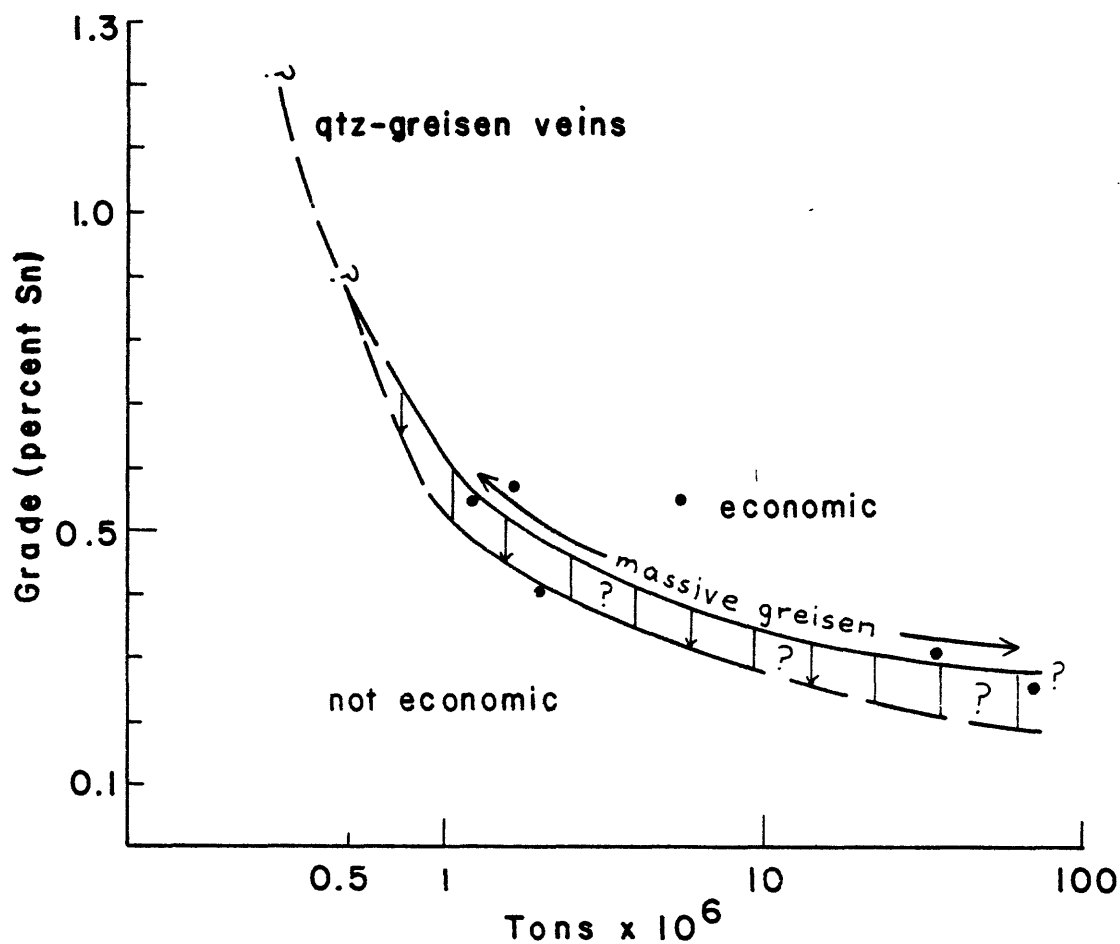
Grades range from a few ppm in incipient greisen to 0.4-0.6% Sn in massive greisen. Grades in quartz + greisen bordered veins are erratic; locally, veins contain up to a few (1-3?) percent tin.

Tonnage and Distribution with Grade (see preliminary tonnage-grade curve)

Disseminated massive greisen deposits presently mined Australia run between $1.5-7 \times 10^6$ mt at 0.4-0.6% Sn. Questionable figures for deposits in the Erzgebirge district range from $30-80 \times 10^6$ mt tin at 0.2-0.3% Sn. Tin greisen vein and vein swarms (with co-existing metals - Pb, Ag, W, Mo) generally of low tonnage ($<1-5 \times 10^6$ mt at 1-2% tin).

Byproducts

Byproducts from massive tin greisen include: Mo, Be, and W. Upper portions of quartz-greisen vein systems may contain W, Pb, Zn, and Ag.



Preliminary tonnage-grade curve for disseminated cassiterite in massive greisen.

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DIAGNOSTIC FEATURES OF FLUORIDE-RELATED BERYLLIUM DEPOSITS

By
W. R. Griffitts

General

Concentrations of beryllium minerals have been found in nearly all of the epigenetic geologic environments. A possible cause for this promiscuity is suggested by the existence of more than 50 minerals containing beryllium as a major constituent--rather remarkable for a metal that constitutes only a few parts per million of the earth's crust. This multitude of insoluble compounds indicates that there is no problem in precipitating beryllium. The main problem geochemically is to keep it in solution long enough to bring a lot of it together at one place to form an ore deposit.

Regional occurrence

Most concentrations of beryllium minerals in non-pegmatitic rocks are in regions characterized by high-angle faults--most commonly block-faulted areas like our Basin and Range province and Transbaikalia--but also including calderas. The absence of known faults does not indicate the probable absence of beryllium deposits. To illustrate this, the beryllium occurrences in New England were found decades before fault blocks were mapped in the region. Even today some geologists retain the nineteenth century aversion to mapping faults in highly metamorphosed rocks.

Beryllium minerals are very rare in the continental margin areas characterized by steep gravity gradients. Thus, they don't like shallow parts of subduction zones at continental margins. Spreading centers, like other tension zones are more hospitable; the deposits below the African rift valleys with their high Li- and F-waters are doubtless too deep to be economic.

Epithermal deposits are generally in silicic volcanic fields; especially those with rhyolite rich in Be, K, Si, F. Fluoritic intrusive rocks of any depth zone are favorable places.

The beryllium deposits are in fluorite mineralogenetic provinces and might be considered to be details thereof.

Local occurrence

Although beryllium minerals are in districts with major high-angle gravity faults they are not in the faults themselves, but are in minor structures nearby or in favorable strata alongside faults.

The most favorable rocks are those containing much calcite or dolomite. These may be limestone beds, as at Aguachile, Mexico, Iron Mountain, New Mexico, or Lost River, Alaska, or they may be clastic or volcanoclastic deposits containing large amounts of limestone or dolomite debris as at Spor Mountain, Utah. The absence of calcium-rich rocks as potential hosts does not prevent deposition of beryllium minerals. The hypothermal veins in ordinary schist, gneiss and amphibolite at the Boomer mine in Colorado have yielded more beryl than has been gotten at any other mine in the world.

Beryl-bearing granite is a special type of deposit in silicate rocks. The beryl crystals, usually blue, are in rosettes veins, or diverging clusters embedded in apparently unaltered granite and aplite or in fracture-controlled veins that cut the rocks. Several such plutons have both red-weathering and white-weathering facies and in them the beryl is restricted to the white-weathering variety. Replacement bodies of beryllium minerals can form in the wall rocks of plutons where beryl veins or the trend of such veins reach them.

Fluorite accompanies the beryllium minerals in 75 percent of the non-pegmatitic deposits but only in Aguachile, Mexico, and Seward Peninsula, Alaska, and probably Transbaikalia does the rock reach mineable-grade fluorspar. We therefore are mainly involved with accessory fluorite. The beryllian fluorspar deposits may contain fluorite, kaolinite, and bertrandite (Aguachile, Mexico), fluorite and phenakite (Transbaikalia), or fluorite, diaspore, and chrysoberyl (Last River area, Alaska). Established assemblages in other environments are: fluorite, feldspar, and phenakite; fluorspar, beryl, and feldspar or mica.

Occurrences of beryllium minerals accompany most intrusive rocks that have accessory fluorite and should be expected in districts with topaz-or fluorite-bearing rhyolites.

Size and shape

Veins and replacement deposits in well defined, persistent structures and strata commonly are of simple shape, but minable ore shoots within the structure may be lens-shaped, cigar-shaped, tabular, or irregular. The thickness may be anything between 1/4 inch and 60 feet. The quarter-inch veins are naturally of no industrial importance, but they indicate that beryllium was mobile in the district. Formation of an ore deposit then would reflect details in the geologic and structural history of the area which might lead to ore, when deciphered. The longest beryllium ore deposit, at Spor Mountain, Utah, is about a mile in length. The shortest is only a few feet. An orebody does not need to be large to be minable. Ore containing at least 10 percent BeO is priced at \$100 to \$130 per 20 lbs. of contained BeO (\$1000-\$1700/ton for beryl ore in 1982), so a mass of a few tons may be well worth mining.

Mineral composition

Only six of the many known beryllium minerals, beryl, bertrandite, phenakite, chrysoberyl, helvite, berylite, are found in large deposits, but some others probably will be found as ore. Phenakite, bertrandite, beryl, and helvite are the most common primary beryllium minerals. None of the minerals have conspicuous appearances, so they tend to be overlooked. Associated minerals include fluorite, which is usually present; topaz--rather common; quartz; black iron oxide--magnetite, maghemite, or hematite; siderite; a little pyrite; bismuthinite; wolframite; scheelite; cassiterite; rarely base metal sulfides.

Altered rocks associated with the beryllium deposits contain an assortment of minerals that reflects the geologic environment in which they were formed. The contact metamorphic deposits contain a wide variety of silicates of Fe, Ca, and Mg. Some of these tactites are fine-grained, some are coarse. The mineralogy of beryllian tactites is not especially

distinctive though fluorite is common and magnetite moderately common. Some of the rocks have concentric curved layers and have been called orbicular tactite, ribbon rock, and wrigglite and then seem consistently to be beryllium-rich.

The hypothermal and epithermal deposits have K-feldspar and phyllosilicates as persistent associates. Quartz-white mica greisen may be widespread in the hypothermal districts, but it generally does not itself contain very high beryllium values. In many, perhaps most, districts, the greisen formed after beryl deposition, and some of the beryl was altered to bertrandite-mica aggregates, less commonly to phenakite-feldspar mixtures. Euclase probably is widespread in hypothermal deposits.

Many of the hypothermal veins contain much K-feldspar and are so coarse-grained that they have unfortunately been mistaken for pegmatites. Beryl and fluorite are found together in at least three-fourths of the veins, but they are antipathetic in pegmatites, in which phenakite, gadolinite, helvite, or some rarer beryllium mineral is associated with fluorite. Beryl is rare in these pegmatites and where present is accompanied by other beryllium minerals and may be altered to them, leaving pseudomorphs as the evidence of beryl's former presence. The internal structures of the feldspathic veins has little similarity to those of pegmatites. Monomineralic feldspathic masses are common and may be cut by veins of quartz, beryl, fluorite, magnetite, or other younger minerals as in the Baboquivari Range, Ariz. or these and other minerals may form nearly pure fillings from wall to wall of the veins as at Oreana, Nev., but they are not in the arrangements that are common in pegmatites. The veins are less likely to be homogeneous than pegmatites are.

The distinction between veins and pegmatite bodies is not academic. World-wide there is an upper limit of about 1/2 percent beryl in bodies of pegmatite. Individual zones may be higher. There is no such limit for veins, some of which are 90 percent beryl. Extrapolating units below the outcrop for resource estimation must be done with due consideration of the different structural behavior of the two classes of deposits.

Epithermal deposits generally have kaolinite or smectite as the phyllosilicate, and feldspar is present as fine-grained adularia (it may be lacking as at Aquachile, Mex.). The rocks usually are too fine-grained to permit recognition of many minerals in the field; quartz or jasperoid, clay, and purple stains of fluorite being most commonly seen.

The mesothermal deposits that yield so much base metal are strangely scarce among beryllium deposits.

Chemical composition

The associated elements can be divided into three categories: those that form soluble complex ions with fluoride, such as Be, Fe, Mn, W, Sn, Nb, U, Th, Bi, Ti, Si, and rare earth metals; those that aid precipitation of the first group by reducing the fluoride content of the solution, such as Ca and Al; and those that can be in solution regardless of the fluoride content; the most prominent being Zn, Li, K, and Na. Note the absence of most common base and precious metals.

Origin

The group of deposits is defined by presence of fluorides, so fluorine must be involved in the origin. As an amphoteric element, beryllium tends to precipitate from solutions that are not strongly acidic or basic. This tendency can be overcome by complexing the beryllium to reduce its chemical activity in the solutions. Of the many complex ions reported, only those of fluoride (mainly BeF_4^{2-}) and chlorocarbonates seem likely to be involved in hypogene mineralization. High contents of fluoride in a magma can cause beryllium to become concentrated in residual solutions instead of being picked up by plagioclase and other minerals. Similarly, dispersed beryllium in rocks can be mobilized during rock alteration by fluoride-rich solutions and thus be available to be carried through suitable structures to a favorable site for precipitation. Precipitation can be induced by changes in pH, changes in temperature or pressure, loss of solvent, or loss of fluoride from the solution. Reaction with limestone can raise the pH and reduce the fluoride concentration simultaneously by forming fluorite, thus accounting for its particular favorability as a host rock. Reaction with silicate rocks can decrease the fluoride concentration by formation of topaz, fluorite, and fluorine-rich micas.

Appearance in outcrops

The most prominent minerals in outcrops of beryllium deposits are quartz and fluorite. The quartz of the hypothermal veins looks much like the "bull quartz" that has been passed over by generations of prospectors as worthless. The common beryllium minerals are themselves resistant to weathering, but the aggregate of minerals may not be. For example, where one vein of nearly pure beryl at the Boomer mine crossed a gneiss outcrop, it had disintegrated to form a cleft that contained in its soil the loose beryl crystals from the disaggregated vein. Beryl ore bodies in quartz veins thus may show in outcrop as breaks in the vein.

The fluorite in beryllium deposits usually is purple because of small amounts of uranium or thorium in the rock. This is not always the case and pale green fluorite may be close to purple fluorite. Unfortunately, the purple color may be bleached on the outcrop, so the fluorite may be difficult to recognize. In general, any fluorite-bearing clay-rich body should be investigated for possible bertrandite or other valuable minerals.

Coarse-grained ore generally sheds float that excites the interest of an alert geologist because of peculiar textures or minerals. Perhaps accessory calcite is a negative and feldspar a positive factor. Fine-grained ore that lacks colored fluorite probably escapes notice. Evidence of mineralization is then likely to be geochemical.

How can we find them?

A few lucky prospectors have found important deposits by recognizing beryllium minerals in the field. Most often they have been found during laboratory studies of ores of other commodities or by geochemical exploration in geologically favorable places.

Stream sediment surveys are rather effective tools. Dilution of silt (-80 mesh) sediment by wind-blown material must be guarded against in arid or periglacial areas. Beryl, phenakite, and euclase are commonly in coarse particles that are excluded from the samples if +80 mesh material is excluded. Thus both deep seated and surficial geologic environments must be considered carefully in deciding upon sample media and interpreting results. In general, silts containing 20 ppm Be can be considered evidence of mineralization. Ten or even 5 ppm may also be significant in limestone areas with very low "background." Concurrent presence of elements commonly found in beryllium deposits is naturally encouraging. Carefully concentrating the heavy minerals from the sediments can remove bertrandite and beryl while concentrating phenakite, chrysoberyl, helvite, and euclase. Heavy mineral studies thus can be very useful, but finding low beryllium contents in the heavies does not necessarily indicate the absence of beryllium mineralization. If the geology of the study area is favorable the silt and coarse nonmagnetic sediment should be checked for beryllium. Blue or green beryl can often be recognized while panning sediment because its large grains tend to rise to the surface of the pile of material with the other coarse minerals of low density. Phenakite, uncolored euclase, and less common minerals would probably not be recognized.

Beryllium deposits that lack fluorides should be found by the same geochemical techniques.

Working upstream or up hill from a known beryllium-rich sediment or soil sample site will lead to a source area in which one or more of the many types of beryllium deposit may be found. In this respect the procedure is like the traditional one of the old time gold prospectors.

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SPOR MOUNTAIN BE-F-U DEPOSITS

By David A. Lindsey and Daniel R. Shawe

Regional and Local Geologic Controls

The Be F-U deposits at Spor Mountain are the only ones of this type of economic value, but the existence of numerous minor occurrences elsewhere indicates that there is a class of ore deposits that resembles those at Spor Mountain and that additional economic deposits will be found.

Spor Mountain-type deposits should be expected in tuffs, tuffaceous breccias, and associated fault breccias. Host rocks are interlayered with volcanic dome-and-flow complexes of high-silica, high-fluorine rhyolite. Such rhyolites have a high content of alkalis (but are not true alkalic igneous rocks) and commonly contain topaz, although fluorine may be occult in the matrix. These rhyolites are erupted during times of regional block-faulting in extensional tectonic regimes, such as the period of faulting that formed the Basin-Range Province during late Tertiary time. Faults and fault intersections control the locus of rhyolite eruption and mineralization, so that deposits are most likely to occur along high-angle faults and caldera ring fractures.

Deposits are most likely where carbonate rocks are present in the basement beneath the rhyolite dome complex, and have been involved in faulting, eroded and incorporated in tuff, or erupted explosively with tuff. Carbonate rock serves as the host for replacement by fluorine-rich mineralizing fluids at Spor Mountain.

Characteristics of Ore

Ore occurs as layers and lenses in tuff and fault breccia that show extensive argillic (smectite) alteration; such altered rocks display the popcornlike texture seen in bentonite (Lindsey, 1977; Shawe, 1963; Staatz and Griffiths, 1961). Fluorite and silica nodules, formed by replacement of carbonate clasts, and manganese oxide nodules, veinlets, and stains are common. Both ore and host tuff are slightly radioactive, as are associated high-silica, high-fluorine rhyolites. Beryllium minerals (only bertrandite is known from Spor Mountain) are not visible; they are best detected by dissolution of fluorite nodules and X-raying the residues. Yellow secondary uranium minerals and fluorescent uraniferous opal may be visible in the ore or nearby, and locally these may form economic ores of uranium. Fluorspar pipes may occur nearby in the carbonate-rock basement; these may be radioactive.

Genetic Model

The main outlines of a genetic model appear to be well established (Lindsey, 1977; 1981). High-fluorine tuff and rhyolite is erupted through a carbonate terrane, through vents that follow faults formed or reactivated by extensional block-faulting. Fluorine-rich mineralizing fluids rise through the network of faults and vents and permeate fault gouge and porous tuff that contain carbonate clasts. Fluorite replaces the carbonate clasts, lowering the activity of fluorine in the mineralizing fluids and causing metal-fluorine complexes to become unstable (Staatz and Griffiths, 1961). Metals such as

beryllium and uranium, which may be carried in mineralizing fluids as fluoride complex ions, are precipitated from the fluids or trapped (uranium) in the fluorite lattice. Silica may also be a complexing agent for uranium; it precipitates in response to cooling of fluids, so that uranium becomes trapped in opal. Other metals, such as lithium and zinc, may be fixed in trioctahedral smectite. As the mineralizing fluids replace carbonate clasts with fluorite, the pH of the fluids stabilizes in the alkaline range, causing alteration of tuff to smectite and potassium feldspar (stable at high K^+/H^+ even at low temperatures).

Prospecting Methods

Geologic -- Look for rhyolite dome complexes that overlie a basement of carbonate rocks. After such a complex is found, look for topaz or check available chemical analyses for high fluorine and high silica content of rhyolite. Locate tuff beds, vents, and faults by field and photo mapping. Map and prospect with a scintillator, noting radioactive units. Watch for popcornlike clay alteration in tuffs and along faults and search for carbonate clasts and fluorite-silica nodules in tuff; even slightly altered tuff may contain fluorite nodules.

Geochemical -- Sample rhyolite and tuff for fluorine and trace element analyses. Fluorine, beryllium, lithium, cesium, manganese, niobium, yttrium, uranium, and perhaps thorium may form halos around a mineralized area. Molybdenum, tin and tungsten may also be anomalous. Anomalies in fresh rhyolite indicate a favorable magmatic source; anomalies in clay-altered tuffs may indicate mineralized areas.

Geophysical -- No methods known to have been tried.

Economic Considerations

Spor Mountain is the principal source of beryllium for domestic industry; tonnage and grade are company confidential, but have been estimated to be sufficient to provide the United States with beryllium for many years at current consumption rates (about 198 metric tons in 1975) and to average less than 1 percent BeO in grade (Griffitts, 1964). Nearby fluorspar mines have produced 202,500 metric tons of 60-95 percent ore through 1975. A uranium deposit located in the Spor Mountain district produced more than 90,000 metric tons of 0.20-0.23 percent U_3O_8 . Similar geologic environments contain anomalous traces to near-economic amounts of molybdenum, tin, and tungsten. Thus the economic implications of the discovery of another Spor Mountain-type deposit are significant.

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OROGENIC (METAMORPHIC-HOSTED) GOLD-QUARTZ VEINS

By

Johnkarl F. P. Bohlke

This description outlines some broad features common to many moderate-temperature, intermediate-depth gold-quartz- (carbonate) vein deposits of various geologic age which occur in orogenic belts throughout the world. The "orogenic (metamorphic-hosted)" deposits include some of Lindgren's mesothermal to hypothermal vein deposits. They are considered to be different from shallow epithermal bonanza and disseminated gold deposits which are typically young (e.g. Tertiary gold in Nevada and North Island, New Zealand). Also, the gold-quartz veins are considered to represent syn- or postmetamorphic stages of gold concentration which are distinct from stratiform syndepositional stages represented in the Archean mainly by Au-bearing iron formations of carbonate or sulfide facies. It should be noted that long-standing controversies are common with regard to styles of mineralization in districts with metamorphically remobilized stratiform deposits (e.g. Homestake, S. Dakota; Morro Velho, Brazil). Available evidence does not always indicate the relative importance of chemical-sedimentary, metamorphic, or hydrothermal processes in concentrating the gold.

Current genetic hypotheses allow for an essentially complete gradation from stratabound low-grade polymetallic deposits, through metamorphic segregation lodes, to fissure-filling hydrothermal gold-quartz veins with metasomatic haloes (in places including rather large disseminated replacement ore bodies). The characteristics emphasized below are aimed broadly at the epigenetic veins, but should not be taken to exclude other types of gold deposits in similar environments. Other metals which tend to be concentrated in analogous tectonic settings include Sb, W, and possibly Hg; these metals are among those often enriched in the gold-quartz veins.

Major gold-quartz vein deposits occur in Archean greenstone belts (e.g. in the Superior and Slave provinces of Canada; Pilbara and Yilgarn blocks of western Australia; Rhodesian and Kapvaal cratons of southern Africa); and in volcanic-sedimentary orogenic belts of Paleozoic (e.g. Tasman Geosyncline of eastern Australia; on the east flank of the Urals), and Mesozoic (western metamorphic belt of the Sierra Nevada, California) age. Hutchinson (1975) suggests that Proterozoic analogues are relatively rare.

Archean greenstone belt stratigraphy and tectonic history may not be completely analogous to those of Phanerozoic orogenic belts; however, striking similarities in mineralogy of deposits and intriguing common spatial and temporal relationships of mineralization to metamorphism and plutonism suggest that similar processes of gold mineralization may have operated at various times over a 3-billion-year interval.

Regional Setting

Orogenic gold-quartz lodes occur in sheared and folded terrains consisting largely of eugeoclinal-type sediments and volcanics metamorphosed regionally to greenschist (+) facies and intruded by major batholithic sequences. A highly generalized Archean greenstone belt might contain thick sections of mafic and ultramafic rocks with banded iron formation and related chemical sediments, overlain by clastic sediments and more felsic volcanics.

These rocks constitute deformed and metamorphosed septa or pendants of various size in granitic and gneissic cratonal areas (e.g. Barberton, Murchison belts in Kapvaal craton; Abitibi belt in Superior Province).

The Phanerozoic gold-bearing metamorphic terrains often appear to be related to continental accretion or collision near sites of former subduction, and include ophiolitic, island-arc, and various marine deposits, such as argillites, tuffs, cherts, turbidites, and graywackes. The volcanic and sedimentary rocks are intensely deformed by regional compression. Major fault zones are often marked by discontinuous linear serpentinite protrusions. Granitic to dioritic plutons intrude the metamorphic rocks during or following the regional deformation, and are in turn sometimes cut by the gold-quartz veins.

Deposit Characteristics

The lode deposits are variable in form, in part because of differences in the timing and conditions of formation. At Bendigo, southeastern Australia, the lodes take the form of crudely conformable "saddle reefs," which occupy fold crests in the Paleozoic rocks. In the Mother Lode, many of the gold-quartz veins occupy discordant faults with minor reverse displacement. Anhaeusser (1976) reviews evidence from the southern African Archean which suggests that the gold-quartz vein mineralization is largely controlled by fractures in the metamorphic rocks caused by the intrusion of plutonic rocks. These fractures are discordant with respect to the earlier (prebatholithic) regional deformation. In general, folded, faulted, and boudinaged veins and lenses are common, indicating syn- or postmineralization deformation. Packages of locally discordant quartz veins and irregular bodies can occupy major shear zones (e.g. Yellowknife district, N.W.T.; Boyle, 1961) or may appear to be crudely stratabound (e.g. Porcupine District, Ontario; Fryer et al, 1979).

The quartz bodies themselves commonly contain inclusions of altered wall rocks, grading to quartz-filled breccias. "Ribbon structure" and "crinkly banding," which typify portions of some veins are composed of sheared inclusions or wallrock septa, and perhaps pressure solution residues. Repeated reopening, brecciation and cementation of earlier vein quartz, and recrystallization are evident in most veins. Complex syntectonic vein formation may be accompanied by remobilization and multistage deposition of gold and other vein constituents (e.g. Petrovskaya, 1970).

Within veins, gold is distributed either fairly regularly (e.g. ore "shoots" measuring hundreds to thousands of feet in long dimension), or in rather unpredictable small high-grade pockets separated by barren quartz. At Alleghany, California, and in the Bridge River district, B.C., high-grade ore appears to be most abundant near altered serpentinite wall rocks. At Ballarat, southeast Australia, gold ore occurs where veins cut C-rich, or pyrite-rich "indicator" horizons in the metasedimentary wallrocks. Throughout much of the Mother Lode belt in California dark metashales appear to be more "favorable" wall rocks than metavolcanics (Knopf, 1929). In general, because of the relatively deep seated origin, the vein mineralogy and grade do not vary markedly with depth (to well over 5,000 ft in some instances).

Low-grade disseminated replacement ore bodies in metamorphic rocks near veins and fissures have been mined (e.g. in the southern Mother Lode); as have masses of altered serpentinite and granitic rocks with numerous small quartz veinlets (e.g. listwanites and beresites of Russian authors).

Mineralogy

Quartz is the dominant vein mineral, with carbonates (mainly Fe bearing) constituting the bulk of the remaining gangue. Pyrite and arsenopyrite are usually present, along with variable amounts of chlorite, mica, albite, carbon, pyrrhotite, galena, sphalerite, stibnite, sulfosalts, and sometimes molybdenite. Scheelite seems to be abundant sporadically (e.g. Grass Valley, Calif.; Otago, New Zealand). Tourmaline may be more common in deposits formed at the higher temperatures (e.g. Dome Mine, Ontario).

In the veins, gold occurs free in quartz, as inclusions in arsenopyrite or pyrite (possibly also in galena and sulfosalts), and less commonly as tellurides or aurostibite(?). The fineness of the native gold is variable, but generally ranges from about 800 to 950. Silver is the main impurity; other metals, including mercury, may be present in lesser amounts.

Intense carbonatization/desilication is typical of wallrock alteration which extends up to several meters from the quartz veins. Sericite, chlorite, albite, pyrrhotite, arsenopyrite, and pyrite are also commonly abundant in the wallrocks. High temperature assemblages, including amphiboles, biotite, and garnet may be associated with some groups of metamorphosed(?) veins. Boyle (1979) notes a general increase in K_2O/Na_2O and Au/Ag and CO_2/SiO_2 approaching veins in several districts. In ultramafic rocks, intensely altered quartz-carbonate rock with green Cr-rich mica (mariposite or fuchsite) is typically surrounded by a zone of talc-carbonate alteration.

Genesis

Stable isotopic and chemical data suggest that some gold-quartz veins may be metamorphic in origin, the vein constituents having been derived from surrounding rocks during periods of shearing and recrystallization in a low water:rock system (e.g. Boyle, 1961). Other veins cutting regional foliation, with positive trace element halos (e.g. for As, Hg, Sb) and wallrock alteration zones, indicate that vein constituents were often deposited from solutions traveling along permeable channels (post-metamorphic faults). Most of the discordant gold-quartz veins of this type appear to have formed later, and some at lower temperature, than the peak of metamorphism in the surrounding rocks. The process may involve a sequence of events such as: (1) segregation of ore and gangue constituents from source rocks during metamorphism or incipient melting at depth, (2) migration with fluids along fault zones, and (3) hydrothermal deposition at higher levels and lower temperatures, removed from the source. In detail, the development of individual gold-quartz veins is often complex, involving contemporaneous deformation, recrystallization, and remobilization of vein constituents (especially quartz). Most such vein systems probably formed during intermediate to terminal stages of long complex deformational and intrusive cycles in orogenic belts.

The source of gold is variously attributed to metamorphosed gold-rich chemical sediments, greenstones, or ultramafic rocks, or to deep-seated igneous activity. Some workers have suggested that gold-quartz metamorphic lodes could in turn be feeders to second-generation syngenetic gold-rich marine volcanic-exhalative deposits above the metamorphic pile (Hutchinson et al, 1971; Hutchinson, 1975). The repeated association of gold-quartz veins with greenstones and altered ultramafic rocks may reflect either source, tectonic environment, or depositional control as important genetic factors.

Isotopic and fluid inclusion data are sparse. Information from several Archean and Phanerozoic deposits indicates that the main stages of vein formation occur at roughly 200 to 350°C; Kerrich and Fryer (1979) report depositional temperatures greater than 400°C for tourmaline-bearing veins in the Porcupine District, Ontario. Solutions in inclusions in vein quartz have variable but sometimes large CO₂ contents to (to >20 percent by weight). Observed daughter minerals include halite (Henley et al, 1976), dawsonite, micas, carbonate, and albite (Coveney, 1982). Vein quartz $\delta^{18}\text{O}$ values range from about 12 to 22 per mil, implying solutions with $\delta^{18}\text{O}$ values of roughly 6 to 14 per mil. Deposition of gold could take place with decreasing temperature as complexes become unstable. Other workers have suggested that gold is deposited when CO₂ is segregated from the aqueous solution, possibly because of decrease in temperature or pressure. Deposition is apparently enhanced where strong reducing agents are available in the wallrocks to reduce the complexed gold. Clearly much work is needed on both the tectonic relations and chemistry of vein systems in individual districts to test the viability of one or more genetic models for this rather diverse group of deposits.

Prospecting Techniques

Criteria for predicting major lode gold mineralization centers are not well developed, though proximity to possible source rocks (such as mafic-ultramafic rocks or auriferous chemical sedimentary horizons) appears to be important in some areas (e.g. Ridler, 1976; Anhaeusser, 1976). In a few places at least, gold-quartz veins tend to occur in greenschist facies rocks, but not in equivalent amphibolite or higher grade rocks nearby (e.g. Anhaeusser, 1976; Henley et al, 1976). They are generally absent from the interiors of batholiths, but occasionally cut intrusive fringes or outliers in the metavolcanic-sedimentary sections. Roslyakova and Roslyakov (1975) recommend extensive regional surveys to locate large-scale "ore-field halos" of ppb-level Au enrichment.

Quartz veins or any major shear zones within the proper regional setting should be investigated for gold mineralization, especially if placer gold deposits occur nearby. In association with tectonic breaks or major fault zones, areas of carbonatization or sericitization may provide regional clues to gold-quartz mineralization. Magnetic surveys may also be useful in mapping covered metamorphic rocks, especially in areas where serpentinite is an important structural or ore-related feature. For example, large sharp positive aeromagnetic anomalies attributed to serpentinite bodies along fault zones follow roughly the locus of major lode gold production in the Mother Lode, and a strong correlation between high-grade gold and serpentinite exists within several individual districts.

Carbonate alteration may form a conspicuous halo around a vein system. Weathering of Fe-bearing carbonates produces a bright orange Fe-oxide surface on outcrops. Where ultramafic rocks are present bright-green Cr-mica-quartz-carbonate alteration (listwanite) is distinctive. Some lateritic soils formed on carbonate-altered ultramafic rocks in mineralized areas may contain low-grade gold values. It should be emphasized again that the gold-quartz veins may be genetically related to either stratiform chemical sediments or disseminated metasomatic hydrothermal deposits which occur within the same geologic setting. At least a part of future interest in the veins will be directed toward using them as guides to these other large-tonnage deposit types.

Pronounced trace-element halos are often present in vein wallrocks. Arsenic is probably most useful because it typically forms large positive anomalies up to tens of meters wide. Well-developed As haloes have been found to persist in soils near outcropping veins. Au, Ag, Sb, and Hg are also usually enriched in the wallrocks. The occurrence of negative "depletion" haloes near some veins may complicate the local zonation of these elements. Other elements may be consistently enriched near veins within certain districts, but not universally; these include B, Ba, K, Bi, Te, W, Cu, Pb, Zn, and Mo.

Within veins, gold ore shoots are commonly thought to be localized near such features as vein intersections, rolls, abrupt changes in thickness, or where veins intersect quartz-free fractures. Deposition of gold may be enhanced near serpentinite, carbon-rich, or pyrite-rich wallrocks. In parts of the Mother Lode, coarse-grained arsenopyrite and galena tend to be located near high-grade gold ore. Some Russian studies have correlated the positions of ore shoots with abundance and CO₂ content of fluid inclusions in vein quartz (e.g. Vertushkov et al, 1970; Lyakhov and Popivnyak, 1977). This short list is only a sample of the many diverse empirical "ore guides" used more or less successfully in different districts. It should be noted that fire assays of vein quartz often show only traces or undetectable amounts of gold even when high-grade ore is close by within the same vein.

Economics

The vein gold deposits are of variable grade and size. These deposits range from extremely high grade (up to several percent Au in small pockets) to below the limit of current economic ore grade. The cost of mining vein deposits underground is strongly dependent on local conditions such as geotechnical properties of the rocks, size and predictability of ore shoots, and surface conditions. Furthermore, inflation and the variability of gold prices are somewhat unpredictable. Nevertheless, it is probably reasonable to guess that a sustained lode gold mining operation would require on the order of 0.1 to 0.5 oz/ton ore, which is roughly the same as that of most major mines in the past. Numerous small profitable high-grade veins have been exhausted after very small production, whereas a large number of 1,000,000+oz deposits have supplied an important part of world gold production, particularly in the Archean occurrences. Some rich districts (e.g. Alleghany, California) have had a long production history despite the fact that ore is erratically distributed in high-grade pockets which have not been successfully mapped in advance of production.

Anhaeusser (1976) estimates total gold production from the Archaen greenstone terrains of Canada, Brazil, India, western Australia, and southern Africa to be on the order of 400,000,000 oz, or slightly less than half that of the Witwatersrand. For comparison, the State of California has produced over 100,000,000 oz of gold (Clark, 1969) of which roughly 90 percent came from placers and lodes associated with the Sierra Nevada and Klamath Mountains metamorphic belts.

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VOLCANIC EXHALATIVE MASSIVE SULFIDE DEPOSITS

By
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Warning

This presentation addresses only massive sulfide-type deposits enclosed in predominantly volcanic sections (the proximal volcanic environment) and does not deal with bedded ores in black shales that may have numerous thin tuff beds of constant thickness over long distances (the distal environment).

Regional Setting

As the title would suggest, volcanic exhalative massive sulfide deposits always occur in a predominantly volcanic section but with variable amounts of mudstone that is usually tuffaceous. That the rocks are volcanic is often hard to prove. Shards, of course, are most helpful. Apparently these volcanics and ores are also always in the submarine environment although it is common to try to prove cases for fresh-water deposition. There may exist a few such examples, but the ore fluids are commonly 300-400°C for the economic deposits. In order for such fluids to empty out on or close to the rock-water interface, at least 2000 m of ocean water or equivalent is needed to keep the ore fluids from boiling and thereby depositing their loads in the subsurface "framework" environment. It is therefore important to prove both a volcanic and submarine environment. Many U.S. geologic maps do not separate volcanics into submarine and subaerial categories so areas labeled as volcanic terrains probably will need field checking. The normal types of evidence looked for are pillows, algal structures, and less reliably, high values of Na/K (greenstones, green tuffs) throughout the geologic column and marine microfossils (radiolarians, conodonts, forams) in the Phanerozoic. The microfossils may also be helpful in establishing depth of sea water. Within the submarine volcanic belt, the deposits commonly cluster at very close to one stratigraphic horizon so, if one deposit is known, the probability is high that more deposits exist, perhaps 10-15 or more. The highest probability of finding them is to explore at the same stratigraphic horizon. The precise reason for this localization is not known (Paul Barton has suggested for one possibility that the plumbing conditions were probably not right prior to the major ore-forming event and the source regions were depleted in their available metals after it.) In belts containing abundant basaltic or andesitic volcanics and with bimodal volcanics at the top of the pile, the best ores are highly localized in the silicic volcanics. Valuable deposits are known, however, in dolerite-mafic volcanic-mudstone terrains--or ophiolite assemblages--although the largest of these (on Cyprus) is almost 35 million tons of ore in contrast to the largest deposits in bimodal terrains of about 150 million tons (Kidd Creek, Bathurst, Flin Flon, "kuroko" deposits of the Hokuroku basins etc.). The key in both cases is to look for signs of tensional tectonics such as bimodal volcanics or sheeted dolerite dikes.

Deposit Characteristics and Field Geologic Prospecting Technique

Sulfides are in lens-shaped bodies, highly variable in diameter (500 m is a good size) and comprised of predominantly fine-grained (micron-sized) minerals unless the bodies have been sheared. In such cases, the five most abundant sulfide minerals (pyrite, pyrrhotite, chalcopyrite, sphalerite, and galena) can all look black and be hard to distinguish. The overall appearance

of the fresh ore in bright sun is one of a steel-blue cast. Often some recrystallization has occurred because of continued hydrothermal activity in the mineralized zone resulting in sparse coarse grains of the minerals that aids mineral identification. The overall appearance is often of massive sulfides although in thin section much silicate and other minerals are present (perhaps 30%). Galena and sphalerite are normally concentrated in the upper part of the ore deposits, with pyrite, pyrrhotite and chalcopyrite in the lower parts. The mineralization may be very siliceous in the lowest parts. Often galena will be rare or absent, however, and sphalerite may be the economic mineral that predominates in some deposits with chalcopyrite predominating in others. Stringer zones of pyrite and chalcopyrite can often be found beneath the ore but are also often obscure. Such zones seem to contain much alteration with abundant quartz and magnesian chlorite in the Phanerozoic deposits but ferruginous chlorite without quartz in the Precambrian. The magnesium chlorite can easily be missed in the field because it does not have the characteristic dark-green color and looks more like sericite. If you can recognize the alteration in the field, alteration halos are much larger than the ore deposits and can be useful in telling if you are near a deposit. They may extend 10 or so half-widths lateral to the ore deposit (2-3 km for a deposit 500 m in diameter) and even as much as 500 m above the deposit (including chlorite) although the strongest alteration seems to be beneath the ore deposit. Alteration above the deposits in the Precambrian seems to be less common than in the Phanerozoic and the zones are thinner when they occur. Much work remains to be done on alteration; however, the presence of Na-montmorillonite helps distinguish the hanging wall from the footwall in "kuroko" ore deposits of Japan as Na depletion is a characteristic of the alteration beneath ore. Some less reliable guides are the presence of anhydrite and gypsum or barite at the lateral margins of Phanerozoic deposits, carbonates (often enclosing the deposit) in Precambrian deposits, and sometimes ferruginous capping on deposits of any age. In some areas, tourmaline can be characteristic of the footwall alteration zone. It should be emphasized that none of these characteristics listed are always found. For example, neither anhydrite/gypsum, barite nor ferruginous silica capping nor tourmaline are known in the West Shasta mining district in California. In many deposits, the cap rock may be basalt (often the largest deposits) or mudstone (the smallest) for reasons that still are unclear, but a waning of the silicic volcanism often seems to accompany the formation of many of the deposits. Canadian geologists also look for an impermeable unit (such as quartz porphyry) with a permeable unit beneath (acid agglomerate or coarse pyroclastics which are the so-called "mill rock"). The agglomerate unit is said to be always found within a kilometer of a massive sulfide deposit with the coarsest phase nearest the deposit. Underlying the permeable unit is an intrusive core of either a silicic (most common) or mafic character. Naturally, to see the whole sequence, the section would have to be turned over on its side or fortuitously dissected or faulted, but knowledge of the sequence can greatly aid in telling whether one is above or below or lateral to an ore deposit.

The above discussion dwelled on massive sulfide deposits in low rank or unmetamorphosed terrains. Higher ranks of metamorphism and deformation can result in unusually difficult mineral evaluation problems. In the ore, pyrrhotite abundance increases. Sphalerite may react with aluminous silicates to form gahnite (ZnAl_2O_4). Perhaps most often, the volcanics become layered quartz-biotite-oligoclase gneisses. Mudstones may become black schists.

Basalts become green schists or amphibolites. If shearing is great and metamorphic grade is high, rhyolite domes may take on a granitic appearance. The ore deposits become stretched out and perhaps stand on end giving a small target. The Mg-rich chlorite is likely to survive; however, the alteration zone with Fe-rich chlorites will often be converted to assemblages of hornblende, biotite, cordierite, and anthophyllite. More calcareous zones will, of course, be converted to calc-silicate rocks. Siliceous volcanics may be mistaken for metaquartzites, but quartz eyes may give a clue for volcanics. It can be a real challenge to tell if you're in a volcanic section at all, much less a submarine volcanic section. Even in relatively high rank metamorphic terrains, some evidence may exist, however. Sometimes shard shapes are preserved as well as graded- and cross-bedding. Sometimes coarse clast shapes are preserved in fine-grained units. Often reliance is needed on major element determinations, but even these may not be conclusive, and arguments among professional scientists may go on for years.

Genesis

A gross model for the genesis of volcanogenic exhalative massive sulfide deposits is well worked out. The details are still being worked on. An intrusion into a permeable volcanic pile sets up a circulating cell permitting ocean water to circulate down section and mix with an unknown amount of magmatic fluid component. The resultant fluid mixture is heated to 300-400°C and reacts with whatever units the cell is in contact with. The fluid moves toward the intrusion and is jetted up fractures into the overlying ocean water that is at least 2,000 m deep. Tensional tectonics opens the system to allow the circulating cell system to operate. Some perceive the large area of zeolitized volcanics that form the matrix of the "kuroko" ore deposits of Japan to be the recharge area for the hydrothermal systems. Certainly the pictures of "black smokers" from 21° N. on the East Pacific Rise give great credence to the "jetting" action and possible syngenetic deposition of sulfides (though currents there sweep the fine particulate matter away). The ore fluid is therefore perceived to be an evolved seawater that is a product of reaction with rocks traversed and some unknown component of magmatic fluid. From sulfur isotope studies, the source of sulfur seems to initially be contributed more from rocks leached by the hydrothermal fluids and increasingly from sea-water sulfate as the source rocks become depleted. At the end, the solution becomes oxidizing with resultant deposition of ferruginous silica. Some strontium isotope data indicate an important source of strontium from sources other than seawater or volcanic rocks suggesting the cells may penetrate the basement. Lead isotope data also support sources other than volcanic rocks (the ultra-low lead content of seawater makes it an implausible source).

Additional Prospecting Techniques

Geophysical -- The massive sulfides in the Ladysmith-Rhinelander volcanic belt in Wisconsin were first picked up by airborne EM which is particularly useful for these kinds of deposits and can "see through" the glacial till.

Geochemical -- Bald Mountain, Maine, was picked up by soil geochemistry registering anomalies through something like 300 foot of till. At Crandon, WI, the anomaly is said to be offset to the south of the deposit.

Lithogeochemistry-petrography-isotopes -- To the best of my knowledge no deposit has yet been discovered as a result of any of lithogeochemistry, petrography, or isotope studies. The alteration halos around deposits are substantial, however, and there is no reason why success cannot be obtained. The lithogeochemistry and isotopic signatures (both strontium and oxygen) correlate well with the alteration. The field geologist might profit from a "Coleman-type" mobile petrography unit. Lithogeochemistry and isotopes might aid in distinguishing where you are in relationship to an ore body. The footwall is decidedly depleted in Na, Rb, and Sr and enriched in Mg and sometimes K so staining techniques may be of use. There are indications that the most lead-rich rocks are well above the ore deposit (perhaps 100 m) and most depleted rocks just above the ore deposit or in the footwall. Unfortunately, the whole ball game tends to be in the lead concentration range of less than 20 ppm and a rapid, precise, inexpensive analytical technique would be needed for such work.

Economic Potential

The economic potential of volcanogenic massive sulfide deposits is very significant and their high grade makes them attractive from environmental and energy conservation standpoints. The copper production of the largest deposits can be similar to medium-sized porphyry coppers. The reserves of zinc in the Crandon, WI, and Bald Mountain, Maine, deposits are immense. Kidd Creek is the world's largest silver producer. They can also be an important source of lead.

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- NOTE: Also watch for an issue of Economic Geology on the Kuroko Ore Deposit Project to be published late in 1982.

CYPRUS-TYPE VOLCANOGENIC MASSIVE SULFIDE DEPOSITS IN OPHIOLITES

By
Randolph A. Koski

Introduction

Ophiolite is defined (GSA Penrose Conference, 1972; Coleman, 1977) as an assemblage or sequence of mafic and ultramafic rocks that include, from bottom to top: an ultramafic complex consisting of harzburgite, lherzolite, and dunite, usually with a pervasive tectonite fabric; a cumulate section of peridotite, pyroxenite, and gabbro; a sheeted diabase dike complex; and basaltic volcanic complex, largely pillowed. Isotropic gabbro and plagiogranite intrusions occur at intermediate levels below the sheeted dikes. The sequence is often overlain by pelagic sedimentary rocks such as chert, shale, and limestone. Ophiolite complexes are interpreted (although there is still some controversy) as allocthonous fragments of oceanic lithosphere and upper mantle that were generated during seafloor spreading and subsequently uplifted onto (obducted) and incorporated into orogenic belts along continental margins during convergent plate interaction. Complete ophiolite sections have dimensional, geophysical, and stratigraphic similarity to layers 1, 2, and 3 of the oceanic crust and the depleted mantle immediately below the Moho (Coleman, 1977).

The upper part of ophiolite sequences, particularly the pillow lavas, host a distinctive class of volcanogenic mineral deposits, commonly referred to as "cupreous pyrite" or "Cyprus-type" deposits. For convenience, the latter appellation will be used during this discussion. Cyprus-type massive sulfide deposits in the eastern Mediterranean region have been exploited for copper, gold, iron, and sulfur for over 4,000 years. The largest and most thoroughly studied deposits of this type are found in the Troodos ophiolite massif in Cyprus, but many other important deposits also occur in ophiolite terrane in Oman, Turkey, Italy, Iran, Soviet Union, Scandinavia, Philippines, British Solomon Islands, Newfoundland, British Columbia, Costa Rica, Guatemala, and the United States (Oregon, California, Nevada, and Alaska).

Deposits range in size from a few thousand tons to 20 million tons, but deposits over 5 million tons are unusual. Clusters of individual deposits occurring together may account for high tonnage estimates recorded in the literature. For a massive-sulfide-type ore, the average base-metal content is low; with some exceptions copper grades range between 0.5 and 5 percent, zinc between 0.1 and 3 percent. Although cobalt is locally concentrated in some deposits, and may reach 0.35 percent, it is generally at levels near 0.01 percent (Constantinou, 1980). Gold and silver average between 0.01 and 1 ounce/ton and 0.1 and 2 ounces/ton in massive sulfide, respectively (Bear, 1963; Hutchinson, 1973).

Occurrence

Cyprus-type sulfide deposits represent hydrothermal mineralization at ancient ocean spreading centers, and in a physical sense are a composite of syngenetic massive sulfide mineralization in mafic volcanic rocks and epigenetic stockwork mineralization in lower volcanic and diabase dike complexes of ophiolites. Massive sulfide occurs as concordant tabular, lenticular, or saucer-shaped bodies in pillow lavas or pillow-lava breccias; they may occur at any level within the pillow lava section. The maximum dimensions for large deposits (e.g., Skouriotissa and Mavrovouni in Cyprus) are length, 670 m; width, 210 m; and thickness, 50 m (Constantinou, 1972). Sulfide mineralization in stockwork systems underlying massive sulfide generally extends downward into the sheeted dike complex. The stockwork zone is pipe-, funnel-, or keel-shaped with decreasing vein density with increasing depth below the massive sulfide body. The Limni deposit in Cyprus produced nearly 20 million tons of ore with a grade averaging near 1 percent Cu, all from stockwork mineralization in diabase and gabbro (Adamides, 1975). The massive and stockwork sulfide zones are thought to represent mineralization at the seafloor-seawater interface and in the underlying feeder system, respectively.

Massive sulfide deposits in ophiolites tend to occur in clusters of closely-spaced deposits. For example, numerous deposits located along the northern flank of the Troodos massif are clustered together in groups spaced 7.4 to 12.5 km apart. Within groups, deposits are spaced 2.0 to 4.5 km apart (Solomon, 1976). Recent studies by Adamides (1980) indicate that massive sulfide deposits in the Kalavassos district of Cyprus are spatially associated with, and in several cases bounded by, steep normal faults or grabens. The faults appear to be premineral and may have served as avenues for hydrothermal solutions; the long and relatively narrow massive sulfide bodies of the Kalavassos district may have been deposited in shallow basins created by the faulting. It should be noted that recently discovered sulfide deposits on the East Pacific Rise at 21°N, Galapagos spreading center, and Juan de Fuca Ridge are spatially associated with tensional graben-type faulting.

COMPOSITION AND TEXTURE OF MASSIVE SULFIDE AND RELATED MINERALIZATION

The sulfide assemblage in Cyprus-type deposits is characteristically simple: abundant pyrite or, less commonly, pyrrhotite with minor marcasite, chalcopyrite, and sphalerite. Chalcopyrite is generally ubiquitous, but may increase somewhat in the upper levels of the massive sulfide body (Constantinou, 1980). Sphalerite is subordinate to chalcopyrite, but has an erratic distribution, and may be locally abundant. In a few deposits (Agrokipia B, Cyprus; York Harbor, Newfoundland; Oak mine, Oregon), sphalerite is a major constituent of the ore. In the Agrokipia B deposit, Pb and Cd are concentrated in the copper and zinc-rich zone at the top of the massive sulfide lens. Ordinarily, however, other sulfide including galena and bornite are rare minerals in the massive sulfide. Gangue minerals that typically make up a very small percentage of the ore are quartz, chlorite, carbonate, and gypsum.

The mineralogy of disseminated and vein sulfides in the stockwork zone is identical to that in the massive sulfide: pyrite or pyrrhotite is predominant, and chalcopyrite and sphalerite are sporadic but minor

components. Fracture-controlled sulfides are generally accompanied by quartz and chlorite. Disseminated pyrite in the basaltic wallrock between veins results from the replacement of Fe-Ti-oxides. Discordant veins of red jasper are also abundant in some stockworks.

A zone with abundant secondary silica is present in some deposits, and it occurs immediately below the massive sulfide lens (Constantinou and Govett, 1973). In this zone, pyrite (or pyrrhotite) is mixed with quartz, red jasper, or massive cherty material. Many of the deposits in Cyprus, and a few elsewhere, are overlain by a highly oxidized metalliferous sedimentary rock referred to as ochre. The lateral extent of ochre generally coincides with the limits of the massive sulfide lens. Ochre is a Mn-poor, Fe-rich, bedded deposit composed largely of goethite, maghemite, and quartz. Sulfide is present as fine bands and disseminations (Constantinou, 1976). Ochre probably results from seafloor oxidation of the iron-rich sulfide prior to burial. In the British Solomon Islands, laminated ochre overlying massive sulfide grades upward into a compact sinter containing anhydrite, barite, opaline silica, and pyrite that is enriched in Ag, Au, Cu, Zn, and Hg. The sinter is in turn overlain by iron-rich cherts, and manganiferous wad (Taylor, 1974). This succession appears to represent the sequential exhalative deposition of sulfide, Fe-oxide, silica-sulfate, and Mn-oxide facies. Amorphous Mn-Fe-rich deposits (umbers) and manganiferous cherts are common features in the upper parts of many ophiolites. Their genetic relationship to sulfide mineralization is still uncertain. The presence of Mn-Fe stockworks underlying some umbers, and the mineralogical and chemical similarity between umbers and metalliferous sediments along modern-day spreading centers indicate a hydrothermal origin. In Cyprus, umbers appear to have formed during hydrothermal discharge on the flanks of an oceanic ridge (Robertson, 1975).

Massive sulfide in Tethyan ophiolites (e.g., Cyprus, Oman, Turkey) tends to be porous, friable, and conglomeratic. In ophiolitic terranes of the western United States and Newfoundland the sulfide is a more competent rock with a fine-grained-massive, banded, or brecciated appearance. In most deposits, the brecciation appears to result from tectonic processes, but in some localities (Turner-Albright mine, Oregon) the breccia may be the result of volcanic activity.

In thin section, sulfide minerals have colloform, clastic, and metamorphic textures. Pyrite and sphalerite often occur in finely laminated colloform or botryoidal open-space growth forms. These minerals are occasionally interlaminated. Pyrite framboids are associated with colloform pyrite. Clastic textures have cubic or subhedral-granular pyrite crystals packed in a matrix of finer-grained pyrite, chalcopyrite, sphalerite, and gangue minerals. Pyrite clasts may be marginally replaced by matrix minerals. Metamorphic textures such as recrystallization and brecciation are common in dynamically metamorphosed ophiolite belts. Thermal metamorphism may result in remobilization of less refractory minerals such as chalcopyrite and pyrrhotite. Pyrite clasts in deformed sulfide are veined by chalcopyrite. In the Takilma district of the Klamath Mountains in southwestern Oregon, massive pyritic deposits are intensely brecciated while massive pyrrhotitic deposits have coarse-grained granular and foliated textures (Koski and Derkey, 1981). The paragenetic sequence in most deposits is pyrite (or pyrrhotite) and pyrite + sphalerite early, chalcopyrite late. Episodic pyrite mineralization is indicated by pyrite veinlets crosscutting earlier-formed colloform or clastic pyrite.

Wallrock Alteration

Mafic rocks in ophiolite sequences show progressive pervasive alteration to zeolite- and greenschist-facies assemblages with depth. Thus, the uppermost lavas with zeolites (particularly laumontite), smectite, hematite, and calcite grade downward into lavas and diabase dike complex with increasing amounts of chlorite, albite, quartz, epidote, and actinolite. Relict textures in the greenschist-facies rocks are generally preserved. Chemical changes in greenschist-facies rocks include gains in MgO , Fe_2O_3 , and Na_2O , and H_2O , and losses in CaO , SiO_2 and Cu (Coish, 1977; Humphris and Thompson, 1978). Petrological and geochemical evidence indicate that this large-scale recrystallization and metasomatism occurred during high-temperature subseafloor hydrothermal metamorphism of newly-formed oceanic crust near the spreading ridge and lower-temperature retrograde metamorphism away from the axis of spreading (Spooner and Fyfe, 1973; Coleman, 1977; Elthon, 1981).

Wallrock alteration associated with Cyprus-type massive sulfide deposits is largely confined to the underlying stockwork, and is characterized by variable degrees of chloritization and/or silicification. Where the metasomatism is intense, original volcanic rock textures are largely obliterated. Illite and kaolinite may be present, but smectite is absent (Constantinou, 1980). The original opaque minerals in the rock may be replaced by pyrite. Analyses of intensely altered mafic wallrocks from stockworks in Cyprus (Constantinou, 1980) indicate that Ca and Na are strongly depleted. To a lesser degree, K, Al, Ti, Mn, and Ni are also leached from the rock. Fe, S, Cu, Zn, and Co are enriched in mineralized lavas. Si and Mg may be increased or decreased relative to unmineralized lavas. Pillow lavas surrounding and overlying massive sulfide mineralization may have low concentrations of Cu and high concentrations of Zn and Co relative to normal background amounts (Govett and Pantazis, 1971).

Prospecting Guides

Cyprus-type massive sulfide deposits are small bodies with limited alteration halos. They are especially difficult exploration targets in tectonized settings. However, several features that should be considered while mapping or prospecting in ophiolitic terrane are presented. (1) All of the major deposits are associated with pillow lavas or volcanic breccias, but significant tonnages of mineralized rock may occur at deeper levels within the ophiolite. (2) Gossans over massive sulfides are usually strongly developed, and oxidized and leached cappings often mimic the size and shape of underlying massive sulfide bodies. Furthermore, boxwork and oxide coloration indicative of pyrite + chalcopyrite mineralization are generally present in the gossan. (3) Intensely chloritized and/or silicified wallrocks are diagnostic of Cyprus-type mineralization. The altered rocks are usually massive and fine grained, with no original texture preserved. (4) Deposits of small size tend to occur in clusters, and known districts should be examined in great detail. (5) Mn-Fe-rich cherts are indicators of hydrothermal discharge and sulfide deposits may be near, especially lower in the section. (6) Strong epidotization may indicate oxidizing conditions and sulfides will not be present in the system. (7) Deposits may be related to faults and linear distribution of sulfide bodies should be considered.

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ASSESSMENT OF THE POTENTIAL FOR VOLCANOGENIC MASSIVE SULFIDE DEPOSITS IN DIFFERENTIATED VOLCANIC ROCKS--A FIELD GUIDE

By
Robert L. Earhart

Introduction

The following discussion is divided into two parts: (1) Characteristics of massive sulfide deposits, and (2) How to find massive sulfide deposits. The deposits considered in this discussion include those that are formed in an intermediate to felsic volcanic environment. Hutchinson (1973) divided the family of volcanogenic massive sulfides into three types. To this classification I would add a fourth type. These are as follows:

- (1) Pyritic or pyrrhotitic zinc-copper deposits that are associated with intermediate to felsic volcanic rocks. The deposits are most common in Archean and Early Proterozoic greenstone belts and include the Noranda and Kidd Creek deposits in Canada, the Crandon deposit in Wisconsin and the United Verde deposit in Arizona.
- (2) Pyritic lead-zinc-copper deposits associated with felsic volcanic rocks. The deposits are most common in Proterozoic and younger rocks and include the Bathurst deposits in Canada and the East Shasta deposit in California.
- (3) Cupriferous pyrite deposits associated with spilitic mafic to ultramafic volcanic rocks of ophiolitic affinity. The deposits are most common in Mesozoic rocks and include the Cyprus deposits.
- (4) Pyritic or pyrrhotitic lead-zinc-silver deposits included in marine turbidites and associated with fumerolic activity--an example is the Sullivan deposit in Canada.

Although all four types have common features, the first two are most similar, and for the most part, the same exploration techniques apply to types 1 and 2. The remainder of the discussion deals with these types of deposits.

Characteristics of Massive Sulfide Deposits--Types 1 and 2

Massive sulfide deposits that contain significant amounts of copper, lead, zinc, gold, and silver are associated with late-stage volcanic activity in a subaqueous environment. The largest deposits formed in Precambrian and Early Paleozoic time; however, important deposits occur also in Paleozoic, Mesozoic, and Cenozoic time.

The features in common that make types 1 and 2 amenable to similar exploration techniques include:

- (1) Both are associated with the more felsic phase of subaqueous volcanism and are deposited proximal to felsic volcanic centers.
- (2) The shapes of the deposits are similar--stratabound, irregularly lenticular to tabular (although type 1 deposits are commonly larger than type 2).
- (3) Mineral zoning is similar--lead, if present, is at the top, grading downward, zinc becomes more abundant than lead--copper increases in abundance toward the bottom. Lead-rich parts contain significant amounts of silver and copper-rich parts contain significant amounts of gold.

(4) Both types have sharp upper contacts and "root zone" veining below the deposits.

(5) Both have iron sulfide halos lateral to the deposits.

Some differences in the two types, of which the investigator should be cognizant, are:

(A) Type 1 occurs in sequences of volcanic rocks that are up to several tens of thousands of feet thick and mostly consist of mafic to intermediate volcanic rocks. Commonly felsic volcanic rocks make up only a very thin sequence at the top of the volcanic pile or tops of cycles within the pile. Type 2 is associated with relatively thin volcanic sequences that have a proportionately much greater felsic component than does type 1. In both types, the volcanic rocks grade upward from mafic to intermediate to felsic.

(B) Type 1 rarely contains important amounts of lead; type 2 commonly does.

(C) Sedimentary rocks intercalated with and overlying the volcanic rocks in type 1 deposits include abundant iron formation, ferruginous cherts, and volcanogenic iron- and silica-rich greywackes. In type 2 deposits, the associated sedimentary rocks commonly include minor iron formation, graphitic schists, and carbonate rocks.

The host rock in both types of massive sulfide deposits is usually the more silicic volcanic end member. Rarely in type 1 deposits, the massive sulfides are in andesitic rocks near the contact with overlying more silicic rocks. Commonly the host rocks are of pyroclastic origin, and in unmetamorphosed to upper greenschist terranes they appear as gray to pink felsic rock with "quartz-eye" phenocrysts or as layered tuff that consists dominantly of quartz fragments. In highly metamorphosed terranes, the host rocks lose much of their original character and appear as light-colored gneisses and schists that are siliceous and contain a variety of high-grade metamorphic minerals.

*The sulfide mineralogy of massive sulfide deposits is simple. Pyrite is the dominant sulfide mineral in unmetamorphosed to upper greenschist terranes. In this setting, pyrrhotite may occur in the lower parts of the deposits. In deposits in highly metamorphosed terranes, the dominant sulfide mineral is pyrrhotite. The iron sulfides commonly make up 60 to 80 percent of the deposit. The lead, zinc, and copper minerals are generally galena, marmatitic sphalerite, and chalcopyrite, respectively. In highly metamorphosed deposits, the principal zinc-bearing mineral is commonly gahnite, a zinc aluminum oxide. In all type 1 deposits copper, zinc, and gold are the most important elements. In type 2 deposits either lead, zinc, or copper can be the most important element; silver is most important in lead-rich deposits and gold in copper-rich deposits.

*A great variety of sulfide minerals have been reported from various massive sulfide deposits. This discussion deals with the dominant sulfide minerals prevalent in most deposits.

Polysulfides in the ore body grade laterally into rock containing only iron sulfide. The resulting iron sulfide halo is usually many times larger than the ore body. The iron sulfide minerals are increasingly abundant towards the ore body.

Although termed "massive sulfides", the ore zones may have either a massive or layered appearance, depending on the total sulfide content. Deposits that are about 60-70 percent sulfides or less have a layered appearance. With increasing sulfide content they take on a massive appearance. Quartz is the most common gangue mineral in both massive and layered deposits. In Precambrian deposits, the sulfides commonly have a cataclastic texture--the hard iron sulfide minerals are fragmented, and the softer lead, zinc, and copper minerals are plastically deformed.

Alteration associated with massive sulfide deposits is most intense in the "root zone" and mostly consists of chloritization, sericitization, silicification, and tourmalinization. Rocks lateral to the deposits are commonly chloritized and sericitized. Because chlorite and sericite are also products of regional metamorphism, it is often difficult in the field to discern alteration associated with the deposit, particularly if the "root zone" is not exposed.

Massive sulfide deposits rarely occur alone; rather, they occur in clusters. Therefore, if one deposit is known in the region, there is a high probability that there are others. The task is to find them.

How to find a massive sulfide deposit

- (1) Identify and map volcanic cycles, mafic towards bottom, felsic towards the top. Massive sulfide deposits, if present, will be associated with the felsic component of volcanism, including the siliceous volcanic-sedimentary rocks intercalated or at the top of the volcanic pile.
- (2) Determine if volcanics are subaqueous or subaerial. Massive polysulfide bodies occur only in a subaqueous environment. If subaqueous, the mafic volcanic rocks usually contain pillow structures. The intercalated and overlying sedimentary rocks will be of marine origin--such as iron formation and ferruginous chert.
- (3) Locate the centers of felsic volcanism. In metamorphosed terranes, expressions of volcanic centers, such as calderas, volcanic necks etc., are commonly difficult to identify so that other methods of locating the centers must be applied. In some cases, the felsic rocks are brecciated by steam explosions near the centers, but often such clues are lacking or are not exposed. Felsic volcanic rocks--dacite to rhyolite--are much more viscous at the time of ejection than mafic to intermediate volcanics--basalt to andesite. As a result, the felsic rocks are thicker proximal to felsic volcanic

centers and thinner or nonexistent distal to the centers. Carefully map the various volcanic rocks and compile an isopach map of the felsic component. The thickest parts of the felsic rocks as indicated by the isopachs should correspond to the volcanic centers--barring structural complications. It is critical to work out the structural chronology and tectonic setting of the region. Pre- and syn-volcanic structures strongly affect the loci of volcanic centers, and post-volcanic structures complicate the exercise described above. If post-volcanic structures are complex, as is commonly the case in orogenic belts, palinspastic modeling may be required to reconstruct the volcanic setting. In Precambrian shield areas (stable platforms) palinspastic modeling is seldom needed. Knowledge of the overall tectonic setting of the region is important because type 1 deposits occur in the deeper parts of eugeosynclines over a thin protocrust and also along the margins of subduction zones. Type 2 deposits occur in oceanic rift environments.

- (4) If the above studies produce positive results, exploration efforts should be targeted in the areas proximal to volcanic centers.

If a massive sulfide deposit is present and has been exposed to weathering, it will form a gossan under most climatic conditions. In the conterminous United States, any massive sulfide deposit with such an obvious surface expression will very likely already have been found, but in Alaska and other remote and geologically unexplored regions it is quite possible to discover gossans formed from massive sulfide deposits. The appearance of the gossan depends on original sulfide mineralogy, nature of host rocks, and climatic conditions. Generally speaking, gossans formed from polysulfide bodies in arid to semiarid climates are typically lenticular-shaped, varicolored (yellows, reds, browns), or dull medium to dark brown. Uniformly-tan gossans are usually formed from iron sulfides only. Gossans formed on a topographic slope under wet season-dry season conditions commonly migrate downslope and cover a large area and do not reflect the size or position of the buried sulfide body.

Lead, if present in the primary deposit, is sometimes anomalously high in the gossan material, but zinc and copper are commonly completely removed (malachite may be present as fracture coatings in the adjacent rocks.) An effective test to determine the nature of the gossan parent is to sample the gossan for gold. If gold is present in detectable amounts, the deposit under the gossan contains polysulfides. Conversely, if none of the samples contain detectable amounts of gold, the deposit very likely consists entirely of iron sulfide. This rule of thumb does not necessarily apply to other types of sulfide deposits, but it seems to be universally true for volcanogenic massive sulfides.

Shallow-buried deposits can sometimes be predicted by observing the abundance of pyrite, pyrite casts or pseudomorphs, and limonite in the felsic volcanic rocks. In addition, the thickness of pyritic zones should be plotted. This is useful in defining a target because the iron sulfide halo is commonly many times larger than the deposit. The pyrite zone is more intense and thicker toward the deposit. As a result, a study of this type can point towards the buried deposit. The great bulk of the halo contains very low amounts of the elements of principal interest--copper, lead, zinc, gold, and silver. Geochemical research is needed to identify indicators in the halo

zone. As far as I know, no deposits have been found by geochemical methods, and the limited geochemical research has produced mixed results. Geochemical methods have perhaps received limited attention in the past because of the outstanding successes in locating the deposits by geophysical methods.

Large massive sulfide bodies that are buried to moderate depths--such as Kidd Creek and Crandon--have been found by electromagnetic geophysical methods. The geophysicists have perhaps enjoyed greater successes in finding massive sulfide deposits than any other type of deposit. In the search for buried massive sulfide deposits, geophysical exploration methods should be routinely applied after all the surface information outlined in the previous discussions has been gathered and compiled. It is important that the geophysical results be interpreted in light of the geology--and geochemistry, if there is a geochemical expression. For example, graphitic rocks, which are an excellent electromagnetic conductor, frequently overlie massive sulfide deposits. If the distribution of graphitic rocks can be interpreted from geologic mapping, it greatly assists the interpretation of the geophysical results.

Aeromagnetic surveys can be of assistance in locating felsic centers, which often reflect as negative anomalies, and massive sulfide bodies, which may reflect as positive anomalies, particularly if they contain significant amounts of pyrrhotite. Again, in the interpretation of the magnetic data, it is useful to know as much as possible about the distribution and nature of the iron-rich rocks that commonly overlie the massive sulfide deposits.

It should be mentioned that gold deposits associated with very late-stage quartz veining have been reported in the mafic volcanic rocks that underlie (usually at considerable distance) massive sulfide deposits. Important gold deposits in the Campbell Red Lakes District of Ontario seem to show this relationship, and I have noted the same relationship in the volcanics of the Yellowknife Group in the Northwest Territories. Highly chloritized rock in contact with the veins may also contain significant amounts of gold. In addition to the gold occurrences being important in their own right, they may indicate elephant country for massive sulfide deposits.

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STRATABOUND PRECAMBRIAN SULFIDE DEPOSITS, COLORADO AND SOUTHERN WYOMING

By
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Stratabound Precambrian sulfide deposits are distributed widely in metamorphic rocks of Proterozoic age in Colorado and southern Wyoming. Many of the old mines and prospects in these deposits date back to the last two decades of the nineteenth century. Most of them, however, did not progress much beyond the prospecting and initial developmental stages, probably because the contents of precious metals in these deposits are lower than were found in some other types of deposits. In recent years, interest in these Precambrian sulfide deposits has been renewed during a very active search for potentially minable resources of base metals. Data presented by Sheridan and Raymond (1977) indicate that representative samples from many of these long-ignored deposits are of a grade suggesting potential importance as resources of copper, zinc, and lead, as well as silver and minor gold.

An attribute common to all of these deposits, whatever their mode (or modes) of origin, is that they were metamorphosed simultaneously with their host rocks during a major period of folding and regional metamorphism that reached its peak during the period 1,700-1,775 million years ago. Evidence for this is seen in a variety of metamorphic textures displayed by the ore-bearing rocks. Also, lead isotope studies on samples of galena from these deposits indicate an age falling in the same 1,700- 1,775 m.y. bracket as determined by radiometric age determinations on their host rocks.

The stratabound Precambrian sulfide deposits can be divided into two categories from the standpoint of regional geologic environment: (1) deposits that occur in terrane that has been regionally metamorphosed to the upper amphibolite facies (sillimanite zone) and locally even higher; (2) deposits that occur in terrane that has been regionally metamorphosed only to the greenschist and lower amphibolite facies. Over 80 percent of the known deposits in Colorado and southern Wyoming occur in the more intensely metamorphosed terrane. Whereas the original character of the host rocks and original textures and structures can be recognized in parts of the lower grade metamorphic terrane, such features are difficult and often impossible to recognize in the more intensely metamorphosed terrane. Although some of the deposits in both types of terrane are very likely volcanogenic (formed syngenetically during deposition of volcanic rocks), the origin of some of the other deposits is not at all certain. In order to avoid becoming embroiled in speculative theories of origin, therefore, we present in this report two nongenetic descriptive models, separated according to the metamorphic grade of the terrane.

Descriptive Model A

Terrane: Upper amphibolite facies or higher.

Geographic distribution: Known deposits occur in terrane that has been metamorphosed to the upper amphibolite facies in the Sierra Madre, northern Park Range, Front Range, Wet Mountains, and part of the Salida region. In the San Isabel area of the Wet Mountains, deposits occur in rocks that have been metamorphosed to the upper amphibolite-granulite transition facies.

Ore bodies:

Size and shape: Access to old mine workings is impossible in most of the deposits and, at best, very limited in a few others. Consequently, very little data are available concerning sizes and shapes. By piecing together scattered bits of information from old mining reports and by interpolating from sizes of dumps, the inference can be made that the ore bodies probably range from small pods to large bodies as much as $n \times 10$ feet thick, $n \times 10^2$ feet wide, and $n \times 10^3$ feet long. Although probably originally discoidal or tabular in shape, tight folding during intense regional metamorphism probably has modified many of the deposits to elongate cigar- or rod-shaped bodies plunging along fold axes. Some bodies are known to be boudined. (See further discussion under "Structural features.")

Tonnage: Ranges from very small to an inferred $n \times 10^6$ tons of ore.

Grade: The average grade of 98 samples from 46 mines and prospects is 2.5 percent copper, 5.0 percent zinc, 0.7 percent lead, and 1.6 ounces of silver per ton (54 grams per metric ton). The average gold content of 49 samples from 32 mines and prospects is 0.02 ounce per ton (0.7 gram per metric ton). Minor amounts of molybdenum, tungsten, nickel, cobalt, cadmium, titanium, and bismuth occur in some of the deposits.

Characteristics of the ores: Most of the ores are characterized by noteworthy concentrations of base-metal sulfides in a matrix composed of the metamorphic minerals of the host rocks. The ore minerals commonly are aligned along the layering and foliation (which are generally parallel), but where the host rocks are impure marbles and calc-silicate gneisses the ore minerals occur in irregularly distributed clots and aggregates. Locally, some of the sulfide minerals appear to have been mobilized to form discordant irregular stringers. At a few mines, notably the FMD mine in the Front Range and mines near Grape Creek in the Wet Mountains, some of the ores are truly massive sulfide (greater than 50 percent sulfides), having a matrix rich in pyrrhotite and/or pyrite. Elsewhere pyrrhotite and pyrite are relatively minor constituents. Some specimens of ore from the Sedalia mine (Salida region), Betty mine (Front Range), and Marion mine (Wet Mountains) consist of over 50 percent chalcopyrite and/or sphalerite. Gahnite or zincian spinel occurs in noteworthy amounts in many of the deposits. Varying amounts of magnetite, ilmenite, hematite, and limonite are found in many of the deposits.

Mineralogy: The ore minerals are dominantly sphalerite, chalcopyrite, galena, gahnite or zincian spinel, and numerous secondaries of copper, zinc, and lead. The mineralogic nature of gold and silver is not known although silver is known to be affiliated with galena in some of the ores. Minor amounts of molybdenite and scheelite occur in some of the deposits. Gangue minerals are the metamorphic minerals of the host rocks together with generally minor amounts of iron sulfides and iron oxides.

Depth: May be at the surface or at any depth in the Proterozoic X rocks.

Lithology of host rocks:

Regional setting: In most areas of high grade regional metamorphic terrane in Colorado and southern Wyoming, the Proterozoic metamorphic rocks consist dominantly of three main varieties interlayered at scales ranging from several tens to several thousands of feet. These

principal rock types are: (1) buff to grayish feldspar-rich gneisses containing variable amounts of microcline, plagioclase, quartz, micas, and locally sillimanite; (2) dark-colored amphibolites and hornblende gneisses; (3) gray schists and gneisses containing variable amounts of quartz, biotite, muscovite, plagioclase, and sillimanite.

Local setting: Interlayered within the regional setting noted above are thinner, less common, and less abundant lithologies that seem to be especially favorable as the host rocks of Precambrian sulfide deposits. These lithologies at many of the deposits include the following rock types in varying proportions: (1) biotite-quartz gneisses and schists containing variable amounts of garnet, plagioclase, sillimanite, andalusite, and cordierite; (2) magnesium-rich gneisses containing variable amounts of light-colored amphiboles (anthophyllite and/or cummingtonite), cordierite, phlogopite, garnet, and magnesium chlorite; (3) impure marbles and calc-magnesium-silicate gneisses containing calcite, forsterite, clinohumite, clinopyroxene, garnet, scapolite, vesuvianite, amphiboles, quartz, and minerals of the epidote group; (4) thin dark-colored amphibolites containing principally hornblende and plagioclase; and, locally, (5) gneisses containing varying proportions of magnesian amphiboles, orthopyroxene, and sapphirine (Raymond and others, 1980). In all of these lithologies, either gahnite, the zinc spinel, or other zincian spinels have been found to be characterizing associated minerals at many of the deposits (Sheridan and Raymond, 1977, 1978). Ranging from pale green to bluish green to dark green and nearly black, and from euhedral (in marbles) to anhedral and skeletal (in schists), these spinels can be considered an important prospecting guide. Likewise, magnesium-rich minerals such as anthophyllite, cordierite and pale-brown biotite (phlogopite) are commonly present in the host rocks of potentially significant deposits. Amphiboles, whether light or dark colored, that have a fibrous or columnar habit are commonly present. Other clues are the presence (even in trace amounts) of pyrite, pyrrhotite, and secondaries of copper and zinc, variably colored as white, greenish and bluish coatings.

Pegmatites are ubiquitous in most of the high grade metamorphic terrane. We have noted that where pegmatites occur in gahnite-bearing and garnetiferous rocks, they commonly contain grains of gahnite and garnet that are somewhat coarser and more conspicuous than the grains found in the enclosing rocks. Recognition of such minerals in pegmatites can lead, therefore, to the identification of host rocks lithologically favorable to the presence of concealed Precambrian sulfide deposits.

Structural features: In all of the areas being considered in this model, the host rocks and the ore deposits have been subjected not only to high-grade Precambrian regional metamorphism but also to several Precambrian episodes of folding. In many areas tight to isoclinal folding has been observed. It seems very important to consider the probability that the shapes of the Precambrian sulfide deposits, whatever their original shapes, have been modified very considerably during folding and metamorphism. Sangster and Scott (1976, p. 189-190) have summarized changes in form that can occur during metamorphism, noting that the ore bodies at Balmat, New York, and at

Chisel Lake, Manitoba, have been changed from a presumably oval form to a linear- or rod-shaped form during medium- to high-grade metamorphism. Even more complex forms of ore bodies, including pinching and swelling (possibly related to boudinage), are reported by Sangster and Scott (1976, p. 190). It seems advisable, therefore, that in any mapping and/or exploration programs involving these Precambrian sulfide deposits that due consideration be given to the probability that many of the deposits may now be rod-shaped in overall form and aligned along fold axes. The search for evidence of the directions and angles of plunge of folds might well be very significant in planning exploratory or developmental drilling programs. Our observations of the sulfide concentrations at several mines suggest that although the overall form of the deposits is very likely rod-shaped, the shape in cross-section is likely to be crescentic. Thus, for example, the deposit at the Greenville mine in the northern Park Range is concentrated in the keel of a syncline and appears to plunge parallel to the axis of the fold. At the Lower Slavonia mine, also in the northern Park Range, a small deposit exposed in a cliff is boudined.

Geochemical data: The results of considerable research on geochemical prospecting methods at the Precambrian sulfide deposits in the Malachite mine area near Idledale, Colo., are described in a report by Huff (1963). That mine served for many years as a training ground in geochemical work for both government employees and students at the Colorado School of Mines. Lyman C. Huff, now retired from the U.S. Geological Survey, and Harold Bloom, now retired from the Colorado School of Mines, also did considerable geochemical research at the nearby FMD mine, a similar Precambrian sulfide deposit in which sphalerite and chalcopyrite occur in a matrix rich in pyrrhotite. They led field trips to the mine and demonstrated geochemical techniques during the 1978 International Geochemical Exploration Symposium.

Stream-sediment samples taken downstream from deposits containing gahnite or zincian spinel usually contain fragments of spinel. These tend to be fine grains, especially where the spinel grains are of skeletal habit in the host rocks. However, the particles are of high density, are collectible in panned concentrates, and are visible upon microscopic examination. It should be noted that standard chemical procedures used for analyzing stream-sediment samples do not put the spinels into solution. Consequently the presence of spinel, unless visually observed, will remain undetected by these procedures. Spectrographic procedures, however, are effective in detecting the zinc in spinels. Also, chemical techniques utilizing sodium peroxide fusion are very effective in detecting the zinc in spinels.

Moench and Erickson (1980) have noted that the presence of anomalous amounts of tungsten in panned concentrates from the Sangre de Cristo Range in New Mexico suggest possible stratabound scheelite deposits peripheral to likely hosts for massive sulfide deposits. Because scheelite occurs in some areas in Colorado in Precambrian deposits spatially related to Precambrian sulfide deposits, it seems very likely that panned concentrates collected in some areas of

Colorado may contain scheelite. Such scheelite deposits, for example, are found in the Guffey area and in the vicinity of Wilkerson Pass; both of these areas contain Precambrian sulfide deposits. The scheelite deposits in Colorado have been described by Tweto (1960).

Geophysical data: Huff (1963, p. 168-169) reported that in 1938 and 1939 a student class of the Colorado School of Mines discovered a geophysical anomaly east of any known ore at the Malachite mine near Idledale, Colo. Huff noted that the mine operator, using the anomaly data, drove a new adit and discovered a concealed ore body. The deposits at the Malachite mine, now completely covered by a housing development, were rich in pyrrhotite and chalcopyrite and, according to Huff, were particularly suitable for application of geophysical methods.

Geophysical work has been done by at least two companies at various properties they are investigating in Colorado and southern Wyoming, but their results have not been made known to us.

Geophysical methods very likely can be utilized effectively to search for concealed deposits similar to those at the Malachite and FMD mines near Idledale, Colo., because the ores are truly massive sulfide, having a matrix rich in pyrrhotite. However, the majority of the known Precambrian sulfide deposits in high grade metamorphic terrane in Colorado and southern Wyoming are of the type that have a gangue composed predominantly of silicates. Since such bodies may be conductively discontinuous, they probably are more difficult to detect by geophysical methods. Also, if concealed ore bodies are rod-shaped and plunging at moderate to steep angles, they may be very difficult to detect by conventional geophysical techniques.

Descriptive Model B

Terrane: Mostly lower amphibolite facies.

Geographic distribution: Known Precambrian sulfide deposits are spatially related to a Precambrian greenstone belt, long known as the "Gunnison gold belt," which trends northeasterly from the Lake Fork of the Gunnison River for about 30 miles and is as much as 7 miles wide. J. C. Olson and D. C. Hedlund (oral commun., 1977) noted that most of the terrane in the Gunnison region has been metamorphosed to the lower amphibolite facies, but that locally in the western part the grade is somewhat higher where the rocks contain staurolite, kyanite, or andalusite. They noted also that in the eastern part of the region near Cochetopa Canyon the rocks are in the greenschist facies.

Known small Precambrian tungsten deposits with minor copper occur in a small area near Cleora (southeast of Salida, Colo.) where the metamorphic grade is lower amphibolite facies. North and northwest of this area, however, the metamorphic grade changes to upper amphibolite facies.

Ore bodies

Size and shape: Although old mining reports concerning mines in the Gunnison gold belt give some information pertaining to size, the available data are insufficient to ascertain fully the shapes of the bodies. The ore bodies probably range from small pods to large bodies as much as $n \times 10$ feet thick, $n \times 10^2$ feet wide, and $n \times 10^3$ feet long. Although the original deposits presumably were tabular or discoidal, their shapes may have been modified considerably during folding and regional metamorphism. (See further discussion under "Structural features.")

Tonnage: Ranges from very small to an inferred $n \times 10^6$ tons of ore.

Grade: The average grade of 15 samples from 9 mines and prospects in the Gunnison gold belt is 2.5 percent copper, 5.0 percent zinc, 0.3 percent lead, 1.0 ounce of silver per ton (34 grams per metric ton), and 0.1 ounce of gold per ton (3.4 grams per metric ton). Major amounts of arsenic and minor amounts of titanium, molybdenum, and tin occur in some of the deposits. A younger mineralizing event at the Vulcan and Good Hope mines caused introduction of abundant tellurium and formation of native sulfur; selenium is also abundant in the Vulcan deposit, but some may have been redistributed from the Precambrian deposits.

Characteristics of the ores: Some of the ores consist mainly of base-metal sulfides alone or in a pyrite- or arsenopyrite-rich matrix and are truly massive sulfide (that is, greater than 50 percent sulfides). Other ores are characterized by noteworthy concentrations of base-metal sulfides in a matrix composed of the metamorphic minerals of the host rocks. In such ores, the ore minerals together with pyrite and arsenopyrite commonly are concentrated along the compositional layering and foliation (which are generally parallel). Locally, the ores are relatively rich in gold but lean in base metals, occurring in a pyrite-rich, magnetite-bearing quartzite.

Mineralogy: The ore minerals are dominantly sphalerite, chalcopyrite, galena, and various secondaries of copper and zinc. Very locally (as at the Headlight mine), the zinc spinel, gahnite, is present in the ores in terrane that has been metamorphosed to a somewhat higher grade than the lower amphibolite facies. Although silver is probably present in some of the ores in tennantite, its mineralogic nature is not known completely; it may be affiliated with galena in some of the ores. Likewise, the mineralogic nature of gold is not known in the Precambrian ores, although at the Vulcan-Good Hope mines a younger mineralizing event superimposed on the Precambrian deposits has resulted in deposition of gold- and copper-bearing tellurides. At the Midland mine, where an assay indicated about one ounce of gold per ton, the gold may be in native form, but petrographic data are not yet available. Some of the deposits contain major amounts of pyrite, arsenopyrite, and/or magnetite. Some deposits contain minor amounts of pyrrhotite, marcasite, tennantite, berthierite, molybdenite, ilmenite, rutile, hematite, gahnite, and cassiterite (?). Gangue minerals are the metamorphic minerals of the host rocks together with variable, in some places dominant, amounts of pyrite and/or arsenopyrite. P. A. Drobeck (written commun., 1981) also observed carbonate in two of the deposits.

Depth: May be at the surface or at any depth in the Proterozoic X rocks.

Lithology of host rocks: Eight of the nine deposits examined in the Gunnison region are in the belt of metavolcanics known as the Dubois Greenstone, and one deposit is in metasedimentary terrane. Of the eight which are in the metavolcanic belt, three are in hornblende schist and amphibolite (originally basaltic and andesitic lavas), four are in felsite and felsite porphyry (originally flows and tuffs of rhyolite, quartz latite, and dacite), and one is in a bed of magnetite-bearing quartzite (originally sea-floor chert). At the Denver City mine, one of the four in felsic metavolcanics, the mineralization is restricted to a fragmental facies of quartz-eye rhyolite tuff (P. A. Drobeck, written commun., 1981). A group of five deposits in the Powderhorn quadrangle appears to be strung out parallel to contacts between felsic and mafic metavolcanics and to the abundant thin beds of magnetite-bearing quartzite. Phyllite and schist at the mine in metasedimentary terrane probably originated as argillite, siltstone, and graywacke.

Structural features: A factor that may be very important to the exploration for and the development of ore bodies in the Gunnison region is the presence of tight folding. Examples of tight folding were observed in samples of both ores and host rocks during our own reconnaissance studies. In one sample, the sulfides are concentrated along the fold axis as a rod-shaped body that is crescentic in cross-section. More recently, detailed mapping by Drobeck (1979, p. 24, p. 113) in the western part of the Gunnison gold belt has demonstrated the presence of closely spaced, shallow plunging, tight to isoclinal folds. In the Iris area in the eastern part of the belt, Afifi (1980) has mapped a steeply plunging tight syncline. It is very possible that folding may have modified some or all of the deposits to shapes similar to that observed in hand specimen, that is, rod-shaped bodies that are crescentic in cross-section but possibly great in down-plunge length. Planning for exploratory and developmental drilling in any area probably should utilize whatever information can be determined about the dominant plunge directions and angles for folds in the immediate area.

Geochemical data: The geochemical patterns found to be most useful in mineral exploration in the Gunnison region have been described by Drobeck (1979, p. 149-153). Drobeck found that copper commonly forms a large dispersion halo, especially in the stratigraphic footwalls of the deposits. He found that lead, zinc, gold, silver, and selenium have narrower halos, being closely restricted to the sulfide-bearing horizons.

A factor that might be considered in future work in this region is the presence of major amounts of arsenopyrite in some of the deposits. Geochemical prospecting might therefore utilize arsenic anomalies.

Geophysical data: Airborne geophysical exploration using EM was done by one company in the mid-1970's in the Gunnison gold belt, but resulted in detecting only a very limited number of significant anomalies, these being in an area containing known closely-spaced deposits. Their geologists agreed that if the ore deposits are plunging rod-shaped bodies, they would be difficult to detect by conventional geophysical techniques. At least one other company has done some geophysical work in the Gunnison gold belt but their results have not been made known to us.

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ZINC-RICH MASSIVE SULFIDE DEPOSITS, NORTHERN CORDILLERA:
SOME PRELIMINARY EXPLORATION GUIDES FROM THE
WESTERN BROOKS RANGE, ALASKA

By
Paul K. Theobald, Jr.

The deposits are massive, microcrystalline, stratabound sphalerite with somewhat coarser (up to a few mm) galena. The rock has the appearance of glossy gray shale, and about the same texture. It is dense, heavy to the feel, and soft, rarely exposed at the ground surface. The deposits are usually not large, measured in tens of meters plan dimensions and a meter or so in the cross-strata dimension. (Howard's Pass is apparently an exceptionally large one.) The grades are high. I have heard 40 percent zinc and 15 percent lead mentioned for reasonable drill intercepts. In areas of post-ore structural complexity, such as the thrust belt of the Brooks Range, these ores are mixed with "more typical" coarse-grained breccias, stockworks, veins, pods, etc.

These deposits are best exemplified by the Howard's Pass deposit in the Yukon. Numerous others are known in and around the Selwin Basin in northern B.C., the Yukon, and the Northwest Territories. Several similar deposits have recently been found in the western part of the Brooks Range in Alaska. Even though the literature on these is not extensive, as most of the detailed information is being held confidential by the several competing exploration companies, I have attempted some preliminary guides because there are at least favorable terranes in the Cordillera from the Bering Sea to central Sonora, Mex.

1. Geology

- A. Devonian, or Mississippian, chert/shale sequences provide the host rocks.
- B. Volcanic rocks may be present though the volcanics are usually found after the fact in order to allow a fit to the volcanigenic model. (Some would prefer a Red Sea Brine model, others prefer not to model at this stage.)
- C. Bedded barite is usually found in the stratigraphic column near the ores. This barite is very difficult to recognize in the field, but has been mapped in the DeLong Mountains and around Red Dog.
- D. Massive pods of barite and barite in veins have been reported with some deposits that exhibit secondary mobilization.
- E. Coarse sphalerite (megascopic grains) or galena in either pods, veins, or breccias may be found where there is secondary mobilization.

2. Geophysical

- A. Gravity has been used by Dave Barnes to define the barite pods and he suggests this method may be useful for the sulfides themselves.
- B. Electrical methods have been tried by the companies (both EM and IP) with unknown success. Mutterings about permafrost suggest they were not too successful in the arctic, but both methods should have potential farther south.

3. Geochemical

- A. Stream-sediment zinc (regional) and lead (local) have been the major exploration tools. At least one company is automatically drilling detailed stream-sediment anomalies while following up with other methods.
- B. Soils, using lead as the pathfinder, are supposedly less reliable.
- C. Veinlets of quartz in float can be used with zinc, lead, cadmium, manganese, and silver where some secondary redistribution has occurred.

4. Isotope Studies

Harrover and Norman (1980) recommend a combination of oxygen isotopes and grain size in the cherts.

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BELT STRATABOUND CU-AG

By
Jack E. Harrison

Regional Setting

Stratabound Cu-Ag ores and occurrences are found in white to buff or pale-green quartzites, in green strata in red-bed sequences, and in minor amounts associated with stromatolites. Ore occurrences known to date are in Revett quartzites of the western part of Belt terrane in deltaic, channel, and perhaps bar facies. Green-bed occurrences are marginal to submarginal in resource potential to date but are widespread throughout Belt terrane in tidal flat to shallow shelf facies of the Ravalli and Missoula Groups. White quartzite channels, lenses, and thin (less than 1 m) layers in green argillitic beds commonly contain sulfides in areas where green beds also contain anomalous sulfides.

Deposit Characteristics

Sulfides are in lens-shaped bodies that tend to be in certain formations or strata (stratabound) but that transect strata grossly (not stratiform). Sulfides are predominantly in white, gray, or green strata rather than in red, purple, dark gray, or black rocks.

Mine/Outcrop Characteristics

Sulfides are dominantly bornite, chalcocite, and digenite with lesser amounts of chalcopyrite, tetrahedrite, and covellite. Minor amounts of molybdenite, wittichenite, native silver, magnetite, pyrite, galena, and barite have been reported from some occurrences. A few occurrences are dominantly chalcopyrite.

In detail, the sulfides tend to be concentrated in sedimentary features--in cross strata, at the base of graded beds, in silty laminations in argillitic rocks, in mud cracks, and in fluid escape structures. Disseminated sulfides are intersertal between grains in the rock, but larger clots are clearly late in the rocks and replace silicate or carbonate grains, rock clasts, and cements. Sulfides also occur along small diagenetic fractures as well as major faults that cut the strata. One part of the major known ore deposit (Spar Lake) has sulfide along bedding plane shears that are probably related to thrusts of Cretaceous-Tertiary age.

Spar Lake ore is clearly zoned from an inner core of bornite-chalcocite through successive shells of chalcopyrite, galena, and pyrite.

Outcrops of units that contain anomalous sulfides can be difficult to identify where chalcopyrite is missing or rare. The black sulfides can be very finely disseminated and show no malachite, azurite, or brochantite or only isolated specks visible with a hand lens.

Genesis

These stratabound ores and occurrences are still not defined in a genetic model. Lead isotopes and loss of permeability during Precambrian metamorphism combine to show that the sulfides were deposited in the Proterozoic, but some redistribution both in Proterozoic and Phanerozoic time seems evident. Permeability is a factor obvious from both megascopic and microscopic study of occurrences and ores. Occurrence of sulfide in diagenetic features such as fluid escape structures suggests that the earliest possible time of deposition is late diagenetic. Sulfur isotopes are plus and are reasonably uniform for a single ore body or occurrence, which also suggests that the sulfides are not derived directly from sea water at a "syngenetic" site but have been homogenized during leaching and transportation through the rock. Paleohydrologic transport of metals in both fresh and connate waters appears important for various occurrences and ores.

Prospecting Techniques

Geologic -- break bunches of quartzite and green beds; be suspicious enough to get analyses of rocks with unidentifiable dark streaks and specks.

Geophysical -- none reported as successful.

Geochemical -- a signature of anomalous Cu - Ag - Hg+Mo - Bi - Pb - Ba.

Economics

The one ore body being mined is reported to contain 60 million tons of ore containing 0.7 percent Cu and 1.6 oz Ag per ton. Other ore bodies are being drilled out.

In terms of submarginal to marginal resources, both the quartzite and green-bed occurrences have several billion tons in scattered small to moderate bodies of rock that contain about 0.3 percent Cu and perhaps 0.3- 0.5 oz Ag per ton.

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SULLIVAN-TYPE STRATABOUND PB-ZN-AG

By

Jack E. Harrison

Regional Setting

Deposit is in a turbidite facies of the middle Proterozoic Aldridge (=Prichard) Formation of the Belt-Purcell Supergroup. Thick gabbroic to dioritic sills intrude the Aldridge. All host rocks metamorphosed to upper greenschist facies. This stratigraphic unit is found at places throughout the 50,000 mi² Belt terrane in northwestern United States and adjacent parts of Canada and is the lowest formation of the Supergroup. A major E-W crustal flaw appears to trend through the Sullivan area. North-trending faults bound the deposit.

Deposit Characteristics

Ore body is at the base of the middle Aldridge Formation just above a megabreccia and conglomerate. Host rocks are gray turbidites interlayered with evenly laminated black and gray argillites that form marker beds that range in thickness from less than one to several meters. These are varve-like beds that can be traced and identified in outcrop across hundreds of square kilometers. Some marker beds and black argillites in turbidites are highly pyrrhotitic.

Basic sills and a few dikes intrude the turbidite sequence but are not clearly shown to cut or be cut by the ore. They are, however, characteristic of the Prichard Formation throughout its known exposures.

The ore body is more or less tabular, is massive on the west end, and gradually becomes a series of highly continuous strata to the east. Some strata contain alternating Pb and Zn layers that contain small folds that show axial plane cleavage. The ore body has a black tourmalinized zone below and an albitized one above.

Ore body is cut by cassiterite-bearing veins.

Mine Characteristics

Principal minerals are galena, sphalerite, pyrite, and pyrrhotite. Minor constituents include chalcopyrite, arsenopyrite, magnetite, cassiterite, boulangerite, jamesonite, and tetrahedrite.

Part of ore is massive, but part is laminated in continuous layers of 1 km length. Laminated ore contains small fold and boudin structures and alternates with waste bands of metasedimentary rocks.

Distinctly zoned in a domelike system. From the core and basal zone outward is: pyrrhotite; arsenopyrite, cassiterite; galena, sphalerite, silver; sphalerite, galena; antimony-bearing sulfides.

Genesis

Stratabound involving "igneous" emanations.

Precambrian sills associated with the Aldridge Formation are 1430 m.y. old, which is the minimum but approximate age of the deposit.

Lead isotopes are interpreted to represent two-stage crustal lead derived from homogenization of pre-Belt lead from the crystalline rocks that were source terranes for Belt, and then a "hot brine" leaching of that lead from lower Aldridge to form sea floor ores in the middle Aldridge. Sulfur isotopes suggest sea water sulfur as the dominant component of the ore. Ore fluids are believed to have come up fractures and spilled onto a deep basin floor where distal turbidites and pyritic black shales were being deposited. Either abundant sills or a deeper intrusive mass provided heat to drive the fluid circulation, and faults penecontemporaneous with sedimentation provided fluid channels.

Regional metamorphism has raised host rock and ore into upper greenschist facies.

Economics

Grade -- 6 percent Pb, 5 percent Zn, 2.5 oz Ag per ton
Tonnage -- to 1976, about 123 million short tons of ore, containing
7.5 million tons of Pb, 6 million tons of Zn, and 250 million oz of Ag
Byproducts -- As, S, Sb, Sn

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STRATABOUND MASSIVE SULFIDES--DEPOSITS IN AN ISLAND-ARC BELT OF VOLCANIC/VOLCANICLASTIC ROCKS

By
Leslie Cox
Regional Setting

In the Piedmont Province of Virginia in the southern Appalachians, stratabound massive sulfide deposits are found in a nearly continuous belt of felsic and mafic metavolcanic rocks interbedded with lesser amounts of siliceous and pelitic metasedimentary rocks. These rocks are thought to have formed as part of offshore, ensialic, volcanic chains during late Precambrian to middle or late Cambrian time. This northeast-trending belt, 300 kilometers in length, includes the Chopawamsic Formation in Virginia and the James Run Formation in Maryland. The Chopawamsic alone contains the known stratabound sulfide deposits (Gair, 1978a). These deposits coincide with four areas of regional thickening of the formation (Hodder and others, 1977). One of these areas is the Mineral district (east-central Virginia) where the combined deposits contain the greatest known volume of sulfide in the Chopawamsic. Although a variety of volcanic rocks host sulfide mineralization, felsite hosts the large sulfide bodies on the northwest flank of the Quantico-Columbia synclinorium and felsitic layers host sulfide mineralization on the southeast flank of the Arizona syncline (Pavlidis, 1982). Banded quartz-magnetite iron formation is present in a similar stratabound sulfide-bearing belt of metavolcanic rock correlative to and southeast of the Chopawamsic (Gair, 1978b) and might be considered indicative of nearby sulfide. Elsewhere in the volcanic belts of the Piedmont, regional associations between sulfide deposits and barite-rich and quartz-kyanite zones have been made (Gair, 1979). (The deposits in the Chopawamsic Formation are found along the Quantico, Columbia, and Arvonias synclines as shown on the index map from Gair and Slack, 1979).

Deposit Characteristics

The sulfides occur in roughly planar lens-like bodies conformable with the beds (or foliation) of the host rock. Lenses are found both enclosed within a given lithology and lying at the contact of two distinctive lithologies. Sharp boundaries between sulfide and host rock are typical. Generally, a deposit is made of more than one lens. The lenses vary in size, are closely spaced, have distinctive mineralogies, and are 50 to 90 percent sulfide. The sulfide deposits have been recrystallized and possibly locally mobilized and concentrated by regional metamorphism (Gair and Slack, 1978). The presence of staurolite, almandine garnet, epidote, hornblende, and plagioclase $An_{26}-An_{40}$ in the gangue and wall rock places the metamorphism in the amphibolite facies.

Mine/outcrop characteristics

The deposits consist dominantly of pyrite. Pyrrhotite is present throughout the belt but is predominant only at the southern end where the metamorphic grade is apparently somewhat higher (Gair, 1978). Important but subordinate to the iron-sulfides are chalcopyrite, sphalerite, and locally magnetite. Several deposits also contain considerable galena or zones of sphalerite-galena with concurrently high Ag values. Minor amounts of arsenopyrite, tetrahedrite-tennantite, marcasite, mackinawite, molybdenite, gudmundite, electrum, ilmenite, cassiterite, gahnite, bismuth, barite, and

zincian-staurolite have been reported from the Mineral district. Weakly defined metal zonation at the Arminius deposit (Mineral district) is exhibited by a predominantly chalcopyrite-pyrrhotite-magnetite footwall and pyrite-sphalerite-galena-tetrahedrite (Ag)-barite hanging wall. A small lens parallel to the main body has the mineralogy characterizing the footwall. Subparallel lenses at the nearby Cofer deposit are also distinguishable from one another by mineralogy (Craig and others, 1978; Cox, 1979). Due to weathering characteristic of the region, distinctive red gossan caps the near-surface deposits. (Only a remnant of gossan remains unmined in the Mineral district.) Dumps and surface pits of most deposits are badly weathered and overgrown with vegetation. Studies of host-ore relationships have been dependent upon available drill core. Metamorphism has made the pelitic versus volcanic origin of the rocks difficult to impossible to determine by hand specimen.

Genesis

A volcanogenic syngenetic exhalative origin of the stratabound sulfides is supported by the geologic setting of mixed volcanic and sedimentary rocks, the conformable position and lenticular shape of the ore bodies, the mineralogy, and the weakly defined zonation of some of the deposits. The sites of deposition are thought to have been sea-floor depressions adjacent to volcanic sources along the margin of the closing Iapetus basin (Kazda and Hodder, 1978). Vertical and (or) lateral zonation of the base metals in volcanogenic massive sulfide deposits is used to determine the closeness in time and space of deposition to the volcanic source (Hutchinson, 1973). Cu-rich horizons are considered proximal, whereas Zn-Pb horizons are distal to the volcanism (Plimer, 1978). The mineralogy of the massive sulfide deposits in the Piedmont fit into such a depositional model.

Prospecting techniques

Geologic--At the Arminius mine zincian staurolite and gahnite are found in both light (white) and dark (green) pelitic sediments that are in close association with the ore body. Gahnite has been reported as characteristic of many metamorphosed volcanogenic sulfide deposits and should be noted as a potential prospecting tool (Sheridan and Raymond, 1977).

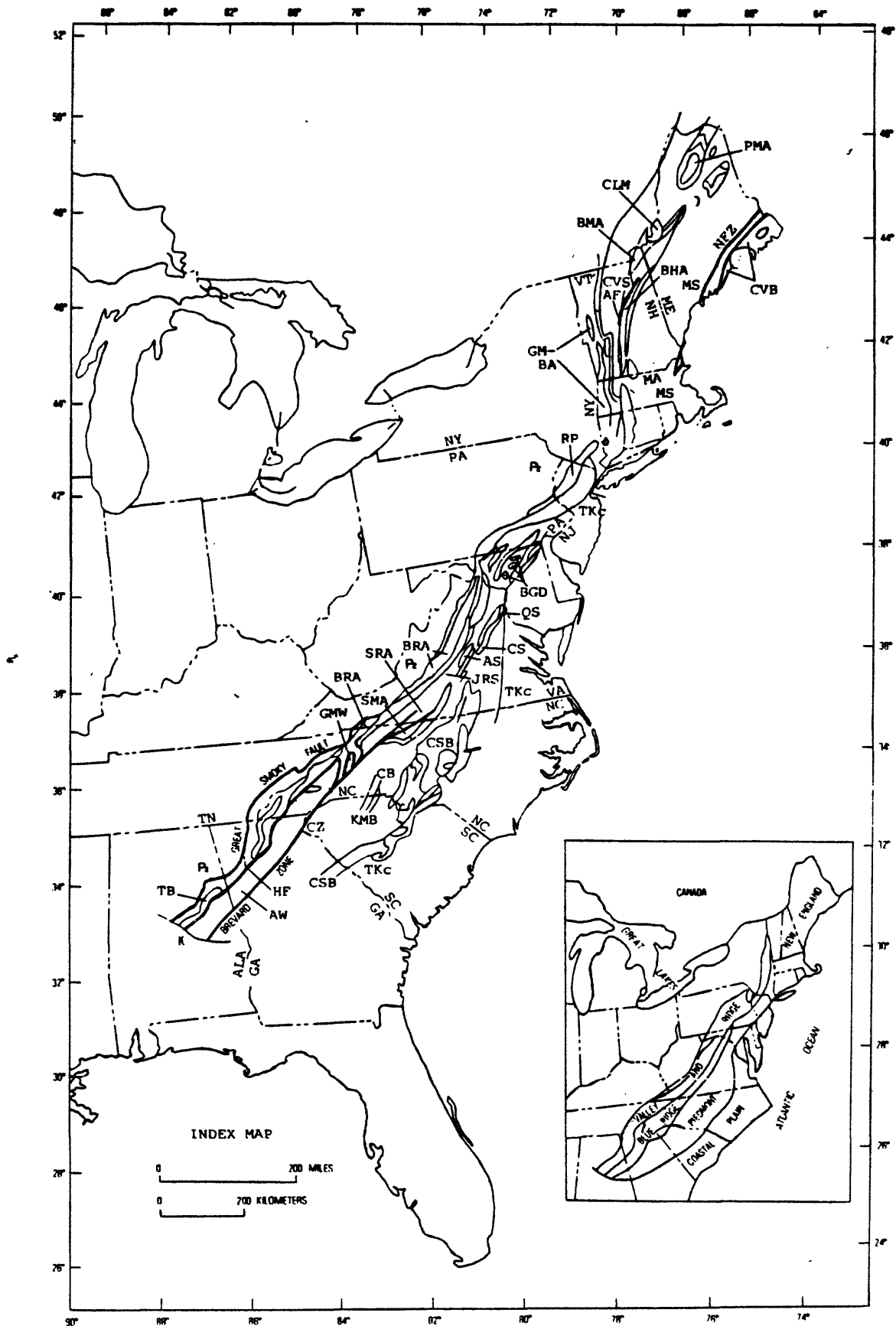
Geophysical--The Chopawamsic Formation, site of the stratabound ores, has a marked magnetic signature (Higgins and others, 1973).

Economics

The sizes of the deposits in the Chopawamsic Formation range from 250,000 metric tons at the Valzinco mine to 10 million metric tons for the combined deposits in the Mineral district. The estimated grades of the deposits are listed along with the weight and other characteristics in table A (Gair and Slack, 1979). The grade at the Mineral district is estimated by Gair to be 1.0 percent Cu, 2.3 percent Zn (locally 40 percent).

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INDEX MAP (Gair and Slack, 1979)

INDEX MAP - Key

New England (NE) Southern Appalachians (SA)

AF	Ammonoosuc Fault	NE
AS	Arvonias Syncline	SA
AW	Ashland-Wedowee Belt	SA
BGD	Baltimore Gneiss Domes	SA
BHA	Bronson Hill Anticlinorium	NE
BMA	Boundary Mountains Anticlinorium	NE
BRA	Blue Ridge Anticlinorium	SA
CB	Charlotte Belt	SA
CLM	Chain Lakes Massif	NE
CS	Columbia Syncline	SA
CSB	Carolina Slate Belt	SA
CVB	Coastal Volcanic Belt	NE
CVS	Connecticut Valley Synclinorium	NE
CZ	Chauga Zone	SA
GM	Green Mountains-	
BA	Berkshire Anticlinorium	NE
GMW	Grandfather Mountain Window	SA
HF	Hayesville Fault	SA
JRS	James River Synclinorium	SA
KMB	Kings Mountain Belt	SA
MS	Merrimack Synclinorium	NE
NFZ	Norumbega Fault Zone	NE
PMA	Pennington Mountain Anticlinorium	NE
QS	Quantico Syncline	SA
RP	Reading Prong	NE-SA
SMA	Sauratown Mountains Anticlinorium	SA
SRA	Smith River Allochthon	SA
TB	Talladega Belt	SA
Pz	Paleozoic undivided	
TKc	Tertiary-Cretaceous Coastal Plain	

BLUE RIDGE MASSIVE SULFIDES

By
Jacob E. Gair

Summary of ore bodies and geologic setting: Pyrrhotitic-pyritic-base metal sulfide deposits in late Precambrian metasedimentary rocks and associated mafic metaigneous rocks--about 800 m.y. old (Rankin and others, 1973; Rankin, 1975).

Two and possibly three distinct Blue Ridge models exist:

- (1) Sediment-hosted; mafic metaigneous rocks that are conformable and contemporaneous with the metasedimentary rocks exist within 500-1,000 feet stratigraphically of massive sulfide; mafic rocks make up less than 10 percent of stratigraphic section.
- (2) Sediment-hosted; no mafic metaigneous rocks located within 1,000 feet stratigraphically of sulfide deposits and possibly no igneous rocks contemporaneous with the metasedimentary rocks exist in the stratigraphic section. 1,000-foot cutoff point arbitrary; types (1) and (2) may essentially be equivalent.
- (3) Massive sulfide deposits within the mafic metaigneous rocks, or at the contact of these rocks and enclosing metasedimentary rocks.

Deposits are tabular, pod-shaped, and S-shaped compact masses of sulfide, rock fragments, and gangue minerals. Massive sulfide deposits are defined as containing more than half sulfide minerals. Pyrrhotite is the principal mineral of most deposits. Pyrite generally is minor, but is abundant in some deposits. Sphalerite and chalcopyrite are almost ubiquitous minor components (1 to 4 percent). Only traces of galena are present in most deposits. Sulfide bodies characteristically are loaded with inclusions consisting of wall-rock and vein-quartz fragments, coarse metacryst blades and sprays of actinolite-tremolite, and small metacryst clots of calcite, 0.5-5 mm in diameter. Sulfide bodies vary in length from a few 10's of meters to as much as 2,000 meters, but probably very few exceed 1,000 meters. Thicknesses of deposits vary from about 1 to 40 meters, and deposits may contain from a few thousand to about 20 million tons or more of ore. Most deposits contain less than 5 million tons of ore, and average about 1 percent Cu and 2 percent Zn. Total massive sulfide in the two largest districts, Ducktown, Tenn., and the Gossan Lead, Va., may exceed 100 million tons each, though much of the sulfide would not be recoverable because of thin or attenuated layers and excessive distances from the surface. Sulfide deposits comprising a district may be closely grouped, occurring within a few kilometers or less of one another across areas up to 30 kilometers wide.

Metasedimentary Host Rocks

Thick sequences of metasedimentary rocks of flysch type or turbidite association. Examples are interbedded sequences of micaceous chloritic metasandstone (or corresponding quartzite and mica quartz gneiss), metagraywacke, meta-arkose, metasiltstone, and argillite or slate. Overall thicknesses of thousands of meters. Thicknesses of individual lithologic units vary from less than a meter to 100-200 meters. Globes of "pseudodiorite" common within biotite-speckled metagraywacke. Argillaceous rocks may be more or less graphitic.

Additional characteristics: Some zones of small angular to rounded quartz pebbles in the metagraywacke. Some graded beds in the metagraywacke. Some occurrences of slate chips in the metagraywacke. Slates and metasilstones may be finely banded.

Note: Such rocks might be considered to be graben fillings deposited near the edge of a continental plate, as a result of crustal tension and spreading (Rankin, 1975, p. 316). Such a consideration, while having no place in an occurrence model, could provide a connection between an occurrence model and a genetic model.

Disseminated iron sulfide (pyrite, pyrrhotite) is common, both in sandy and argillaceous facies, in amounts of less than one-half percent; locally, several percent of sulfide may be present. Disseminated sulfide can generally be recognized by thin limonitic crusts on outcrops, whereas massive sulfide that reaches the surface can be recognized by gossans. Disseminated sulfide is essentially ubiquitous, so there is no localized clue to the existence of massive sulfide given by the presence of disseminated sulfide.

Immediate wall rocks (within 1-30 meters of massive sulfide):

- (1) Micaceous quartzite, metagraywacke schist, and other quartz-mica and quartz-mica-chlorite schists--typical rocks of the overall metasedimentary environment, with no preference of massive sulfide for one or another of these types of rock.
- (2) Unusual phyllitic rock--highly micaceous or chloritic rocks containing relatively little quartz (probably less than 10 percent). Includes silky, silvery muscovite phyllite, mottled muscovite-chlorite-biotite phyllites, green chloritic phyllite, and reddish-brown to greenish-black biotite phyllite. Garnets common; garnets may be clear, of the spessartine type, which are very diagnostic, but are not seen in many occurrences. Plagioclase metacrysts, 1-4 mm in size--commonly are present in the chlorite and biotite phyllites, and have grown across and push aside the chlorite and biotite folia. Coarse clots of chlorite may be present in either the muscovite phyllite or the biotite phyllite. Quartz seams are interleaved with biotite or chlorite folia. Such quartz is unusually clear and vitreous. The dark phyllites are generally in the footwall, whereas the muscovite phyllite is generally in the hanging wall, but there can be some variation in these relationships. The phyllites can exceed 5 meters in thickness--up to about 30 meters, measured from the contact with massive sulfide, especially the muscovite phyllite in the hanging wall, but phyllite thicknesses of greater than 2-3 meters are uncommon. Coarse actinolite or tremolite porphyroblasts form blades or sprays in the phyllites, especially the dark footwall phyllites, in many occurrences, and are highly diagnostic.

- (3) Unusual light-gray to nearly white feldspathic rocks containing more than 50 percent of sodic plagioclase, and commonly, about 80 percent. The feldspathic rock can be nearly massive and nonfoliated to moderately schistose. Scattered flakes of well-aligned reddish-brown biotite are common, and make up from a few percent to about 10 percent of the feldspathic rocks. Quartz makes up from a few percent to nearly half the feldspathic rocks. The feldspathic rocks are present in places in the immediate footwall and are not known to be more than a few meters thick. Pink garnets common in the feldspathic rock.
- (4) Vein or bull quartz. Clear and unusually vitreous to white. May be intergrown with white carbonate. Forms irregular pods up to a meter or so thick, mainly on the footwall of massive sulfide bodies.
- (5) Coarse white carbonate. May form small patches and veins less than 10-cm thick in contact with massive sulfide or within a meter or so of sulfide bodies. May pass into coarse actinolite, tremolite, or diopside, which appear to be products of the metamorphism of the carbonate (Emmons and Laney, 1926, p. 19, 42-44). Highly diagnostic, but because of proximity to sulfide, generally this material and massive sulfide will be observed together, that is, during the same observation.

[Caveat: Within the great thicknesses of flysch or turbidite rocks, I know of no broadly distributed lithologic clue that might tell one he could be near an occurrence of massive sulfide (with the possible exception of "pseudodiorite"). The phyllite and feldspathic rocks would be good indicators of the possible proximity of massive sulfide, once an investigator finds such rocks. However, in the climatic setting of the southern Appalachians, gossans are more likely to be seen much more readily than the phyllite or feldspathic rocks in outcrop. In drill core, or in similar geotectonic settings as the Blue Ridge in other geographic regions having better exposures, the unusual rocks could be useful indicators of proximity to massive sulfide.]

Mafic Metaigneous Host Rocks

Silica content about 44-55 percent; tabular and lensoid bodies conformably interbedded with the surrounding metasedimentary rocks. Well-banded to indistinctly banded hornblende-plagioclase rocks having variable salt-and-pepper granoblastic textures; also, massive hornblende schist, and well-lineated actinolite and actinolite-tremolite-chlorite schists are common metaigneous rocks. The hornblende content of the amphibolite typically ranges from about 40 to 70 percent, whereas the hornblende or actinolite content of the hornblende and actinolite schists is about 70-90 percent. The salt- and pepper-textured amphibolite commonly grades into and is interlayered with light-colored gneiss having from very little to about 20 percent hornblende. Generally in these amphibolite facies metamorphic terranes it will not be readily apparent whether the light-colored gneiss interlayered with amphibolite is metasedimentary or metaigneous.

Mafic metaigneous layers may vary in thickness from 1-2 meters to 50-150 meters, or even thicker in exceptional cases. The thicker mafic bodies are more likely to host massive sulfide, but the thin mafic bodies may be located within 150-300 meters of sediment-hosted massive sulfide bodies, so can be of some use in targeting exploration.

Mafic metaigneous rocks probably represent general zones where there was a concentration of hydrothermal solutions as well as molten rock emplaced, so may mark general zones where massive sulfides are likely to occur, even though such deposits may not be directly related to (i.e., are not in contact with) the mafic igneous rocks.

Immediate wall rocks (within 1-2 meters of sulfide bodies):

- (1) Amphibolite, hornblende schist, or lineated actinolite schist--of the same type comprising the mafic metaigneous environment.
- (2) Biotitic-chloritic phyllite.
- (3) White to pale tan, medium- to coarse-grained carbonate rocks. May form lenses less than 10-cm thick between the typical mafic metaigneous rock and the massive sulfide.

[Caveat: Such thin zones next to massive sulfide are not apt to be observed apart from observation of the massive sulfide itself, so are of limited utility.]

In overall perspective of Blue Ridge settings, in areas of greatest concentration of mafic metaigneous rocks--where such rocks may make up more than 10 percent of the total section locally, massive sulfide deposits are not as voluminous as in metasedimentary environments where the mafic igneous rocks are present nearby, but constitute less than 10 percent of the stratigraphic section.

Chemical and mineralogical changes within 100 meters of massive sulfide bodies--relative to average values in country rock outside the 100-meter zone (Nesbitt, in preparation; Henry and others, 1979).

Chemical:

Increase in S and O content of rocks.

Decrease in mole fractions of Fe (relative to Mg) in biotite, garnet, chlorite, and staurolite.

(Quant. example from Nesbitt's (in preparation) work at Ducktown: in biotite, from 0.62 to 0.19; in garnet, from 0.85 to 0.42; in chlorite, from 0.51 to 0.14; in staurolite, from 0.84 to 0.14.)

Increase in Mn content of garnet.

Increase in Zn content of staurolite (relative to Fe).

Mineralogical:

Disappearance of ilmenite and appearance of rutile.

Disappearance of graphite.

Great increase in chlorite.

Increase in zincian staurolite and near the ilmenite-rutile transition at Ducktown, disappearance of staurolite altogether in muscovite-bearing rocks (within tens of meters of sulfide?).

Replacement of almandine garnet by spessartine within 5 meters of massive sulfide; disappearance of garnet immediately adjacent to sulfide at Ducktown, but possibly not universally.

Appearance of coarse actinolite and(or) tremolite.

Concentrations of nearly pure biotite rock.

Appearance of concentrations of carbonate.

Structure

Host rocks are tilted. Most dip 40-90 degrees except locally on fold crests (Espenshade and others, 1975; Magee, 1968; Espenshade, 1963; Rankin and others, 1973).

Overtured beds and fold limbs are present.
Isoclinal folds may be present.

Evidence of overtured beds most likely to be encountered are thin-graded beds (up to 5-cm thick) and cleavage-bedding relationships. [In Blue Ridge, overturning is to NW (Hatcher and others, 1978); in other areas appropriate to application of a Blue Ridge model, structural directions would vary according to the regional geotectonic location of the area.]

Rocks are generally more or less schistose; in many areas inclined schistosity is the only obvious structure, bedding being obscured and in places transposed by schistosity. On fold limbs, schistosity commonly is parallel to, or lies at a small angle to, bedding. Most common attitude of schistosity is NE strike and SE dip (applicable to Blue Ridge settings) Sulfide bodies are essentially or substantially conformable with schistosity; there may be local and minor crosscutting of schistosity by massive sulfide. On approach to a massive sulfide body, schistosity may deflect from a cross-cutting trend to become conformable with the sulfide body within meters of the sulfide.

Wall rocks and sulfide bodies may be folded in open to tight and isoclinal folds.

Sulfide bodies of greater volume than 5 million tons probably occur only in zones that are sufficiently folded that the deposit contains a fold nose or crest and at least part of an adjoining fold limb; a corollary is that a homoclinally dipping, unrepeated (not isoclinally folded) layer of sulfide probably will not contain more than 5 million tons of sulfide within an area limited enough in extent to be mined.

Massive sulfide bodies contain internal evidence of deformation. Deposits almost universally are loaded with breccia fragments of wall rocks. Common wall-rock fragments are muscovite phyllite, chlorite/biotite phyllite, plagioclase-rich rock, and vein quartz. Breccia is essentially limited to sulfide bodies. Pyrrhotite, the characteristic sulfide of many such deposits, may be strongly deformed, as shown by deformation lamellae in crystals (Henry and others, 1979), by strong foliation surfaces in the massive pyrrhotite, and by "flow through" (Durchbewegung) textures of the sulfide with the wall-rock fragments.

Metamorphism

Metamorphism is in the amphibolite facies, garnet, staurolite, and kyanite isograds (Morgan, 1972).

Coarse actinolite/tremolite occurs close to or within sulfide zones and is highly diagnostic. The occurrence of actinolite and tremolite close to

zones of mineralization limits the usefulness of these minerals in zeroing in from well outside such zones. Heavy-mineral stream-sediment surveys, though, might make use of such amphiboles, as John Slack has suggested elsewhere (In press--or 1982) for tourmaline that occurs close to mineralization.

Sulfide bodies show evidence of metamorphic recrystallization. Triple junctions are common at the boundaries of adjoining pyrrhotite crystals (Henry and others, 1979. Coarse blades and sprays of actinolite and(or) tremolite are almost universal within sulfide bodies. Aggregates of medium- to coarse-grained carbonate commonly are intermixed with sulfide and with the amphibole porphyroblasts and wall-rock fragments. Similar quartz aggregates may be of metamorphic origin, or may be fragments of vein quartz from the wall rocks (or both). Coarse subhedral to euhedral crystals of pyrite are present within some dominantly pyrrhotitic bodies. In the context of the surrounding recrystallized materials, the pyrite too, is probably a product of recrystallization.

[Caveat: As noted for other features near or within massive sulfide bodies, such features are part of the occurrence model, but cannot be of much help in resource assessment or exploration, because they are only observed when one already knows he is looking at a sulfide occurrence.]

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THE GEOLOGICAL ATTRIBUTES OF AU-AG-BASE METAL EPITHERMAL DEPOSITS

By
Byron R. Berger

Introduction

Epithermal deposits form at low to moderate temperature in near-surface environments. The most significant epithermal deposits have been mined for silver and gold. These deposits occur in all host rock types, but historically the most important deposits are found as veins, stockworks, and replacements in volcanic rocks and as replacements and veins in sedimentary sequences. A rigorous classification of epithermal deposits is difficult because of the range of depositional settings, mineralogical variations, and diverse trace-element associations. It is the purpose of this brief communication to deal only with the geological attributes of complex-sulfide silver-gold-base metal vein deposits of the likes of Creede, Colorado; Virginia City, Nevada; Guanajuato, Mexico; and, Chanarcillo, Chile.

Some general features

For the sake of communication, let me first lay out what I mean by "epithermal" then I will put forth what I believe to be the important geological features of Ag-Au vein deposits.

Characteristics that classify a deposit as being epithermal are borrowed liberally from the work of Waldemar Lindgren, Henry Ferguson, and Tom Lovering:

Depth of Formation	Surface to 1000 meters
Temperature of Formation	50°C to 300°C
Form of Deposits	Thin to large veins; stockworks; breccia fillings; disseminations; and replacement
Ore Textures	Open-space filling; crustification; colloform banding; comb structure; brecciation
Ore Elements	Au, Ag, As, Sb, Hg, Te, Tl, U, Pb, Zn, Cu
Alteration	Silicification; argillization; illite-sericite; adularia; propylitization
Common Features	Chalcedonic quartz; quartz pseudomorphs after calcite; <u>widespread</u> illitic, kaolinite-alunite, and/or propylitic alteration
Common Ore Minerals	Native Au or Ag; tellurides; simple sulfides of arsenic, antimony, and mercury; electrum; silver sulfides; sulfosalts, and selenides; complex sulfides and sulfosalts of antimony and arsenic; base-metal sulfides

Epithermal deposits form in the upper parts of geothermal systems. Because of this shallow depositional environment, most of the world's truly spectacular epithermal ores have come from Tertiary-age thermal events, particularly related to Tertiary volcanism. Nevertheless, epithermal deposits were formed during other geologic periods, and there is not always direct evidence of igneous activity.

An exploration model

The most difficult thing to do in developing and using a model for exploration or evaluation purposes is to move back away from individual deposits far enough to see the generalities. Additionally, it is important to think in terms of mineral systems, and we may only be looking at small or minor components. Whenever looking at an exposure of a vein, alteration, or whatever it is important to ask the questions "Is this part of something larger?" or "What type of system am I dealing with, and where am I in this system?" Most mineral districts are made up of many mines, deposits, and occurrences (a mine is not necessarily synonymous with a deposit). Regular patterns often are discernible for systems, and regular, but somewhat different, patterns are also discernible within individual deposits within the system. The Ag-Au-base metal model presented here deals both with deposit characteristics and system characteristics.

The View from Afar

Let's deal with Ag-Au-base metal systems. Differences between individual complex-sulfide vein systems are due to (1) the hydrodynamics of the system, (2) conduit and host rock fracture and permeability characteristics, and (3) host rock compositions. Therefore, there will always be a large number of combinations and permutations of these factors that make each mineral system unique. Nevertheless, I offer two general-case scenarios that fit many of the epithermal vein systems with which I am familiar. Figure 1a shows a system with well-developed lateral zoning as well as some vertical zoning and Figure 1b shows a system with well-developed vertical zoning but only vague lateral zoning. The system-wide characteristics that are important to look for are shown on the respective figures.

All important districts occur within strong, persistent fracture systems such as basin-range type faults, caldera ring fracture zones, caldera-related graben structures, or complexly-faulted or domed areas. The absence of a strong structural trend does not eliminate the possibility of high-grade veins, but should be considered as a less desirable situation. I am prejudiced that the heat source is related to magmatic activity.

Figure 1a. Longitudinal sketch of a hypothetical Au-Ag-base metal system with well-developed lateral zoning patterns (from work of P. Barton, P. Bethke, P. Giudice at Creede, Co.)

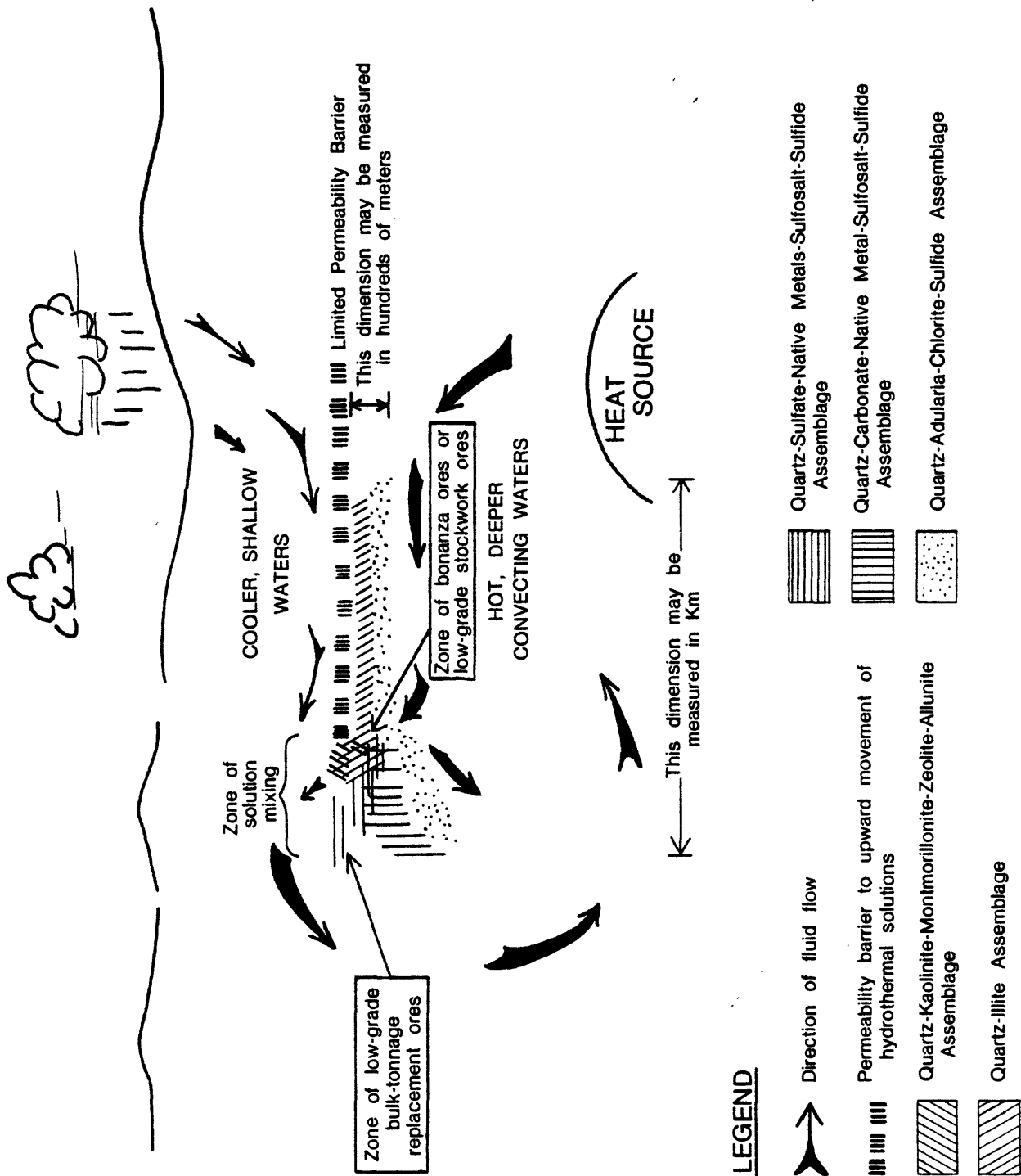
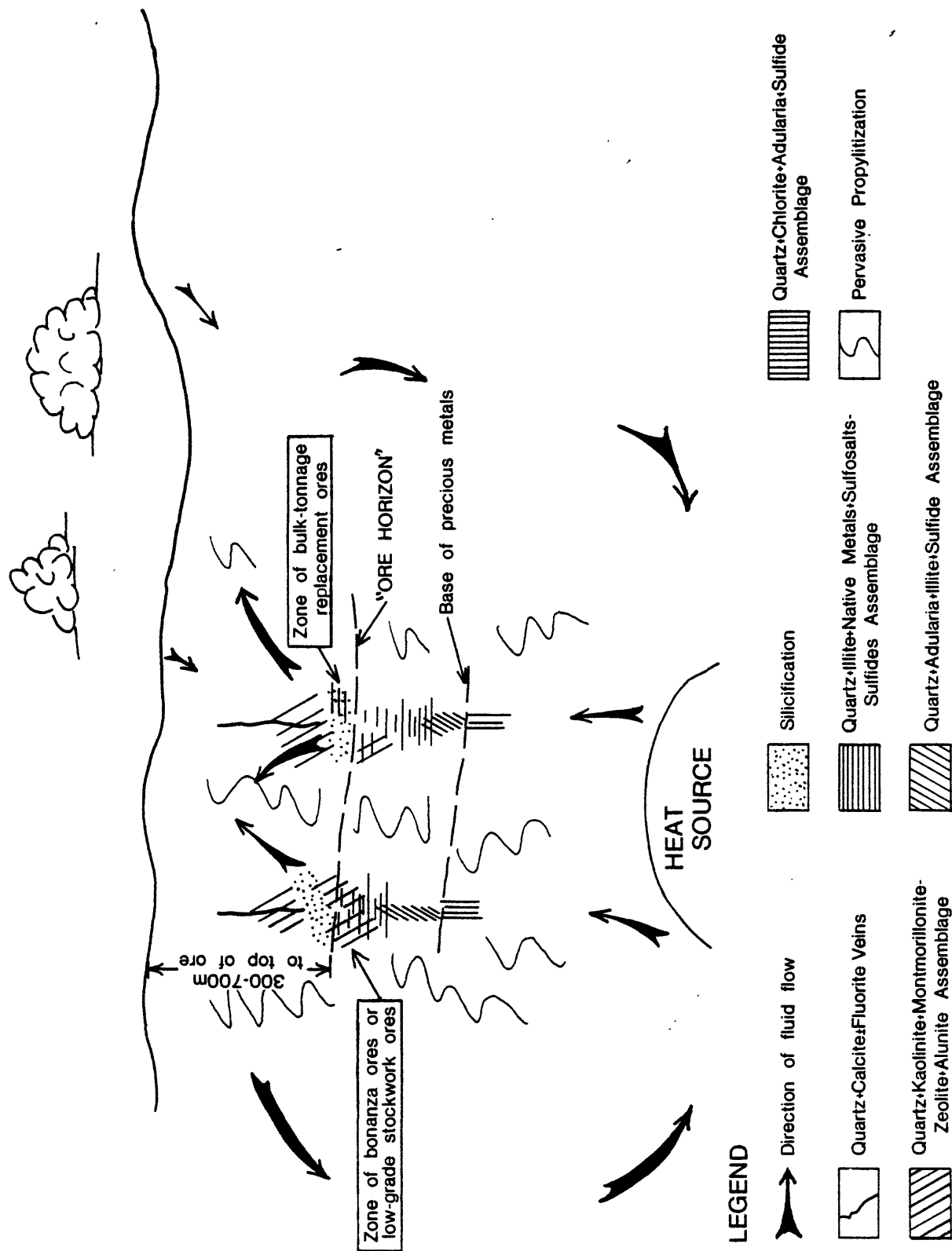


Figure 1b. Longitudinal sketch of a hypothetical Ag-Au-base metal system with predominantly vertical zoning patterns (from work of L. Buchanan, D. White, and others)



The tops of complex vein systems are difficult beasts with which to work, because of the lack of consistency in the alteration patterns above the uppermost orebodies. Nevertheless, let me list some of the more frequent situations:

- (1) Silicification decreasing in intensity to sparse quartz along veins up to several hundred meters above the ore horizon to the surface;
- (2) Narrow fractures with feeble iron oxide and sparse quartz or calcite;
- (3) Strong, barren fracture trend with dikes intrusive along same trend; and,
- (4) Irregular patches of bleaching due to kaolinite and montmorillonite with or without alunite and zeolites.

Any combination of these situations may occur in a given district. One empirical rule: In any given district there is a similar altitude at which most of the orebodies apex. This common altitude is called the ore horizon. Even the least altered fractures can provide geochemical clues to mineralization at depth. The most useful trace elements are arsenic, antimony, and mercury. If one finds small quartz veins with occasional sulfides, then the presence of stibnite might mean pyrargyrite, miargyrite, polybasite or stephanite ores whereas a show of arsenopyrite or realgar might mean pearceite or proustite ores at depth.

Life Along the Vein

In a laterally zoned district the appearance of the vein depends upon where you slice the system. If you look at the zone of solution mixing, then you will see all of the possible alteration-metallization types, and the lateral system will appear most similar to the vertically zoned system. Figure 2a is a hypothetical vein cross-section of this nature.

There is a general decrease in precious-metal values downward on the vein and a general concomitant increase in base-metals. A major change in mineralogy occurs in the vein where there are warps in the fault surface or abrupt changes in strike or intersections with other faults. Hangingwall brecciation is common as are hangingwall splays in the fault system in these places. These are the loci of the very high-grade bonanza ores and/or low-grade, large-tonnage stockwork and disseminated ores. If the vein-bearing fissures transect carbonate rocks, then replacement deposits may result at any level in the system. An additional aspect of carbonate host rocks is that the veins carry calcite (and usually barite) at all levels in the system.

If the vein systems intersect pre-mineral channels filled with sediments, then look for low-grade accumulations of precious metals in silicified or jasperoidal-appearing zones. These sometimes subtle deposits may contain from tens to hundreds of millions of tons of ore compared to the thousands to millions of tons of higher-grade vein ore.

Figure 2b takes a closer look at the interface between quartz adularia + illite and quartz + kaolinite + alunite. Note that acid-leach alteration may occur both above and below the silica capping. The acid-leach argillization or the quartz-illite alteration may be widespread and extend for considerable distances away from the productive fissures. A correct interpretation of what type of alteration you are dealing with is not necessarily straight forward.

Figure 2a. Hypothetical cross-section of a Ag-Au-base-metal sulfide vein deposit.

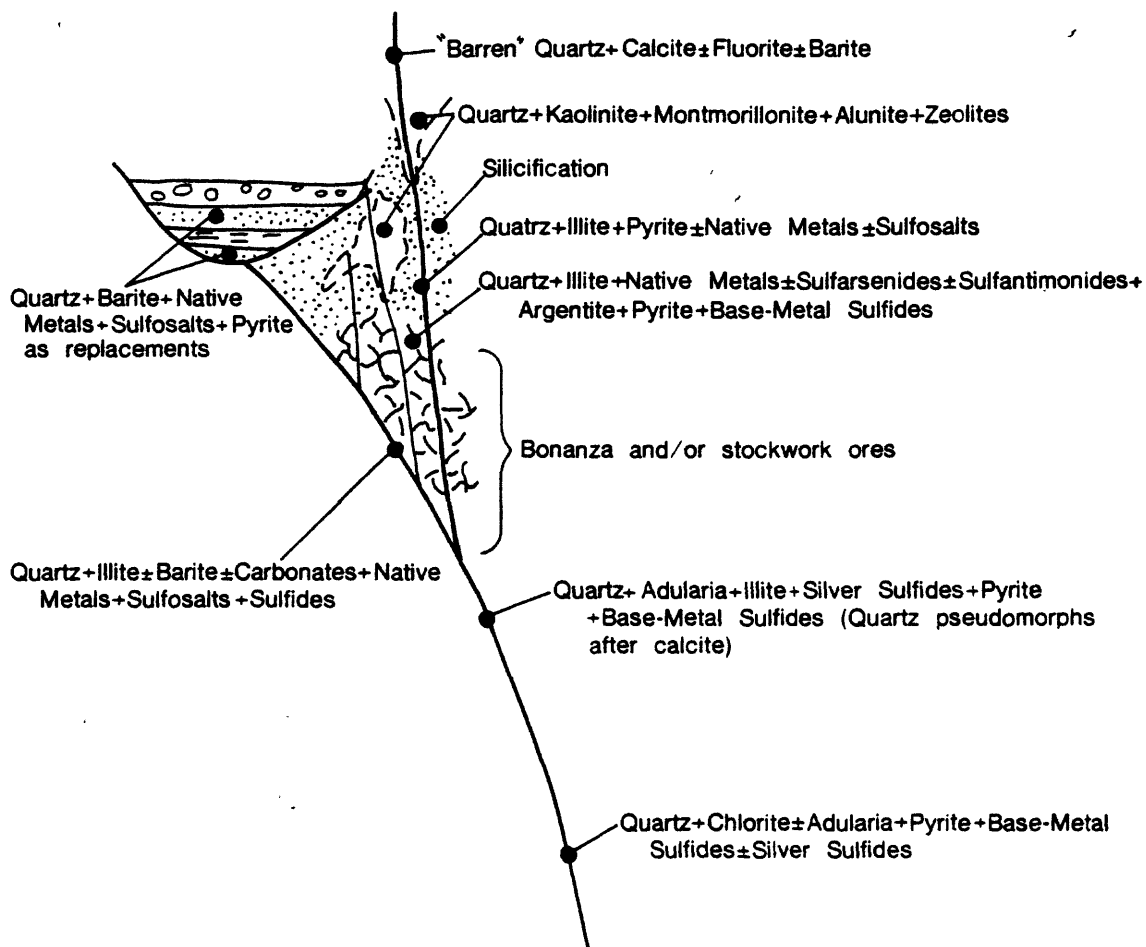
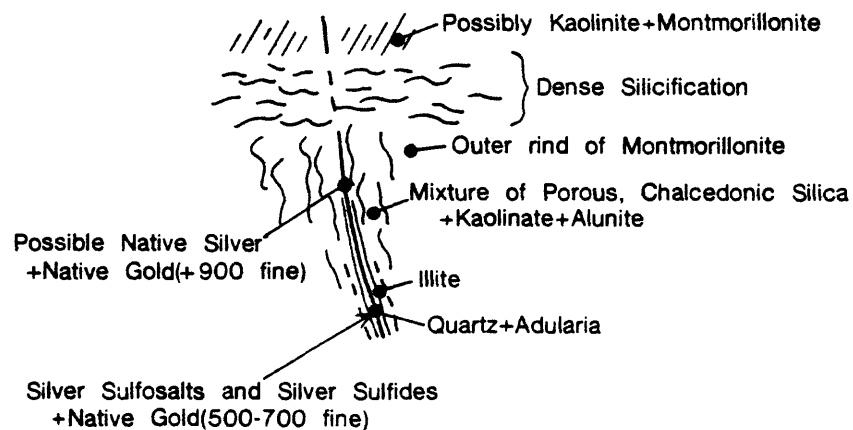


Figure 2b. Schematic drawing of upper part of vein system.



It is usually necessary to use X-ray diffraction to identify the key minerals. Acid-leach alteration is often chalky white if mostly clay, but may be porcelaneous, cherty, or jasperoidal (with a wide variety of colors). The silica is often vuggy or porous. Try to find kaolinite, montmorillonite, alunite, diaspore, or zeolites. Sulfides, predominantly pyrite and marcasite, may be sparse to very abundant (<1%-15%). The quartz-illite alteration normally has a satiny luster and the quartz is very milk-white. However, this alteration can also appear chalky, porcelaneous, or cherty. Look for multiple episodes of quartz veins, white to salmon adularia crystals (often euhedral), quartz pseudomorphs after calcite, mixed illite-sericite, or illite-montmorillonite. Sulfides may or may not be abundant. Look for ore minerals. "Live" or productive quartz is often grayish, blue-gray, or with faint streaks in it. Bull, white, massive quartz is often less rewarding when one is searching for ore minerals. Open-space filling, comb structure, banding or crustification are ubiquitous attributes of epithermal veins.

The deeper parts of veins are easier to deal with, but there may or may not be large alteration haloes around the veins. Look for "live" quartz and adularia. Remember that base metal concentrations increase downward, so if there's no silver in the galena and tetrahedrite is absent you may be too deep. The precious metal zoning is shown on Figure 2a and this pattern occurs in a large number of districts.

The scouring of old dumps for clues to mineral potential is an art as well as a challenge to your hand lens mineralogy. First, not all mines produced ore. Even very large dumps may be wholly from exploration or development drifting (they didn't have diamond or reverse-circulation drills until relatively recently). Second, good miners often segregated dumps as to rock type, trend of vein (usually related to grade or timing of emplacement), or low-grade reserves. Third, watch out for the proverbial promoter's pile of ore, usually placed obtrusively somewhere near the portal or shaft, or a thin veneer of ore coating the dump. The major danger is that the ore was imported from another locality. Fourth, in very large, productive districts they used production shafts, so the ore samples on the dump may have come from almost any level, a considerable distance away along the vein, or even another mine. Nevertheless, dumps from old mines and prospects can provide a wealth of information about the character of the vein, ore mineralogy, alteration types, host rock types, and presence or absence of igneous activity. As a general rule, mines dug in the 1800's and earliest 1900's couldn't treat sulfide ores. So they mined oxidized primary ores or post-mineral supergene ores. Look for gossans on dumps. Examine them for lead carbonate or glassy limonites with a deep red internal reflection. These are indications of earlier, productive sulfides (galena and chalcopyrite, respectively). Lots of yellowish limonites mean a formerly high sulfide concentration. Look carefully at cellular webs of silica and limonite (boxworks) formed from the oxidation of sulfides; small beads or flakes of gold are commonly found within the boxworks. Primary sulfide mineralogies may be read from the cellular structures, but this is an art with few modern practitioners, and the reader should look to the works of Augustus Locke and Roland Blanchard for more information. Sample all sulfide and gossan materials and analyze for gold, silver, arsenic, antimony, copper, lead, and zinc. Even in the good grade sulfide ores the sulfosalts may be very fine grained and unidentifiable with a hand lens. If you can unravel the vein mineralogy look for the general paragenetic sequence of base metal sulfides-tetrahedrite-argentite-silver

arsenides-silver antimonides-native metals. The sequence may be stretched out over a considerable vertical distance or all telescoped together.

SUMMING UP

The alteration patterns, particularly with respect to vein mineralogies, are the keys to this type of deposit. Step back from the individual prospects and look at the whole package. Even if you know you are dealing with a high-grade epithermal Ag-Au vein, you want to know where you are in the vein, and is this vein part of something larger. Use the regional geological framework liberally to get a feel for structural trends and the significance of structures. Use your intuition as to what the types of alteration listed in this model would look like in different types of host rocks. The sequences of alteration are related to processes, and the mineralogies reflect the interaction of these processes with differing host rock compositions.

SILVER/BASE METAL EPITHERMAL DEPOSITS

By

The Creede "family": Paul Barton, Phil Bethke, Pamela Heald Wetlaufer, Nora Foley, Dan Hayba, and James Goss

The model is designed from the Creede, Colorado, mining district. Other deposits thought to be similar to Creede include: Idarado, Colorado; Sunnyside, Colorado; Pachuca, Mexico; and many, many more.

A. TECTONIC/STRATIGRAPHIC SETTING:

- * 1. Large, thick, andesitic to rhyolitic volcanic field built upon a stable craton. Early, intermediate volcanics are capped by quartz latitic to rhyolitic ashflows. Ore deposition took place during time break between the caldera-ashflow cycle and the later, bimodal basalt-rhyolite suite associated with a late-developing extensional tectonic regime. Other San Juan deposits occurred well into the bimodal suite's time span.
2. Veins are found in major graben faults and tension fractures in the core of an older, reactivated keystone graben of a resurgent caldera. Ore-stage structures probably formed in response to the intrusion of a stock below the district. The graben is radial to, north of and younger than the youngest caldera in the caldera complex. Minor veins and "disseminated" mineralization in the hanging wall of a main graben fault have large, but low-grade potential.
3. The wallrock is an intracaldera, welded, ashflow tuff of rhyolitic composition. Prior to ore a pervasive potassic metasomatism added K-feldspar and removed Na. Jasper-cemented, "fluidized" breccia marks the keystone graben structures of an earlier caldera. The older, healed structures were rebroken in part at the ore stage, and they constitute a useful guide to the presence of later, ore-bearing structures.
4. Densely welded tuff is favored over either soft, unwelded or brittle, extremely welded tuff because of its ability to maintain large, open fractures.
5. The ore zone is 4 kilometers long, 2 kilometers wide and 0.3 kilometer in vertical extent.

B. PHYSICAL/CHEMICAL SETTING:

1. Associated wallrock alteration prior to and unrelated to mineralization consists of pervasive K-feldspar "flooding," as noted in A-3 above. Clearly later, but still pre-ore, a second stage of K-feldspar formed selvages a cm or two wide along newly formed fractures. Sanidine in the original tuff remains stable through much of the mineralization.

- * 2. High in the structures, apparently just above the highest silver values, pervasive argillic alteration to mixed-layer illite-smectite attacks all minerals except quartz, producing masses from a few centimeters wide along veins to "caps" on the veins up to several meters wide. At still higher elevations, the illite-smectite envelopes coalesce to form a cap over the entire vein system.

At uncertain intervals during mineralization some of the wallrock was altered to high-Fe chlorite; pumice up to tens of meters from ore-bearing structures shows chlorite development, often associated with euhedral hydrothermal quartz. Chlorite also is common as a vein mineral.

Wallrock is locally silicified, particularly high in the structures in the vicinity of the pervasive argillization. Silicification appears to precede argillization.

3. Vein mineral assemblages show good zonal development from chlorite + quartz + sphalerite + galena + chalcopyrite + pyrite + minor hematite + fluorite + tetrahedrite + adularia to the north and relatively deeper in the veins to barite + quartz + rhodochrosite + galena + tetrahedrite + sulfosalts + sphalerite + native silver to the south.

The early rhodochrosite is low in Ca and Mg but contains up to 60 mol percent siderite. Late siderite is also low in Ca and Mg, and contains up to 60 percent rhodochrosite.

- * Essentially all of the ore is open space filling with banded veins, coarse zoned crystals. Some ore is brecciated ore.

At the southern end of the veins, rhodochrosite plus quartz is the earliest vein filling, overlapped and followed by barite with sphalerite, galena, and silver minerals (mostly tetrahedrite). Wiresilver is late and may be supergene or hypogene; it appears to form from argentite or other silver sulfide minerals. Leaf silver is locally abundant and is of enigmatic origin.

In the northern portions of the veins pyrite, now largely replaced by an early stage of chalcopyrite, was the earliest major sulfide. It was followed by fine-grained sphalerite, galena, chalcopyrite, and silver-bearing tetrahedrite. The sphalerite is generally poor in iron (1 to 3 mol percent FeS) but has some fine growth bands of iron-rich (up to 20 mol percent FeS) growth bands, particularly early in the sequence. Following a period of major hypogene leaching, a minor but distinctive generation of fluorite and siderite was deposited, followed by a coarse grained stage consisting of iron-poor sphalerite, galena, and chalcopyrite (with low silver values). Mineralization ended in both the north and south with fine-grained "gel" pyrite containing minor silver sulfosalts and stibnite.

- * 4. Primary fluid inclusions are abundant; sphalerite, fluorite, and quartz homogenization temperatures are 190 to 270°C, and salinities are 4 to 12 weight percent equivalent NaCl. Analyses show Na/K = 9/1 (atomic), dominantly as chlorides. There are no very high salinities. There are no common daughter minerals. The higher salinities generally correlate with the higher temperatures.
- ** Boiling of the ore fluids is demonstrated by widely varying degrees of filling of coeval primary fluid inclusions and by stalactites of ore. The illite-smectite alteration cap is interpreted as resulting from the re-condensation of acid, volatile components released during boiling. Ore deposition took place approximately 500 meters below the paleo-water table.
- 5. Generally the initial, hydrothermal character of the deposit is retained with no metamorphic overprint and little reaction on cooling from the conditions of mineralization. Supergene processes are not very extensively developed except high in the system. Alunite found high in the system is supergene. Oxidation is active today and unventilated mine workings contain potentially lethal deoxygenated air.
- 6. The chemistry and the light stable isotope compositions reflect interaction of fluids from at least three different sources: one magmatic and two meteoric. The system is relatively oxidized and the overall chemistry is governed by the quartz + chlorite + pyrite + hematite + sericite + K-feldspar + water buffer system.
- 7. Isotopic signatures:
 - Sulfides near 0 $\delta^{34}\text{S}$ per mil with a few very heavy values for late (?) pyrite.
 - Barite from 18 to 44 $\delta^{34}\text{S}$ per mil.
 - O and H show two populations of meteoric water alternatively and repetitively occupying the veins. C, H, and O data strongly suggest a magmatic source for the fluids that deposited the rhodochrosite and siderite.
 - Pb is uniform in composition and is slightly radiogenic, too much so to be derived from local volcanic rocks or their associated plutons. Presumably the radiogenic component is derived from the preCambrian basement rocks.
- C. K/Ar ages on fresh wallrock are about 28 my.
- K/Ar ages on vein adularia and illite-smectite are about 25 my.
- K/Ar ages on supergene alunite are about 5 my.
- D. No distinctive gravity or magnetic signature on ore deposit itself, but both infer a hypabyssal intrusive under the district.

- E. Wide range in grade from rich bonanza silver ore to marginally economic disseminated mineralization.
- F. District potential in the hundreds of millions of ounces of Ag; some Pb, Zn, and minor Cu and Au production.
- G. Mainly a silver district, but with consistent Pb values. The OH and P veins operated successfully with major Pb and Zn production with minor Ag, Au and Cu byproducts.

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HOT-SPRING TYPE, LARGE TONNAGE, LOW-GRADE GOLD DEPOSITS

By

Miles L. Silberman

Introduction

Deposits of disseminated low grade, large tonnage gold and silver in shallow, epithermal to hot-spring environments in carbonaceous, carbonate rocks have been described by many authors and most recently by Radtke and others (1980). More recently large deposits of this type are starting to be developed in rocks other than those associated with the typical Carlin carbonate host rock type. Many of these occurrences have only recently become economic because of the large increases in the prices of gold and silver.

The deposits described here are also shallow, epithermal, disseminated and/or stockwork occurrences of hot-spring origin, but they are not in carbonate host rocks. They occur usually in volcanic and/or volcanoclastic rocks, and generally with a significant felsic component. What follows is based on some literature descriptions (rare for these deposits) including Berger and Tingley's (1980) description of Round Mountain, Wallace's (1980) description of the Sulfur mining district, Bonham and Garside's (1979) very brief description of Hasbrouck Peak and unpublished data on this occurrence (John Livermore, A. B. Wallace, and M. L. Silberman, 1974, 1979) and Russell and others' description of Pueblo Viejo (Russell and others, 1981, in press). References listed above on these occurrences have been digested with the aid of the authors' visits to Hasbrouck in 1974 and 1979, and to Round Mountain and Flowery in 1980 and Sulfur in 1978 in the company of geologists who know much more about this sort of thing than I profess to.

My purpose is to describe some of the characteristics of these deposits that I think are important, in order to establish recognition criteria for the environment that may have economically significant deposits of the hot-spring gold type. Brief genetic connotations that I mention have been organized in my mind by reading the recent work of Clifton and others (1980) and Buchanan (1979, 1981, in press) who have described and suggested models for the classic, epithermal lode-type deposits that many of us have been mulling over for some years. Buchanan strongly emphasizes the genetic connection between the lode deposits and hot-spring processes, a connection that Don White has been stressing for over 25 years (e.g. White, 1955; 1974). Following Buchanan I want to stress here that both types of deposits, carbonate-hosted and volcanic-hosted, form during hot-spring activity and that their genesis is closely tied in to the evolution of a geothermal (also read hydrothermal-- Buchanan, 1978) system.

The model is based on Sulfur, Round Mountain, Hasbrouck Peak, and Bodie and references listed in introduction.

* Denotes especially significant characteristics.

Regional and Tectonic Setting

The deposits that I have seen all occur in the Great Basin in regions that have significant volcanic activity, with a large component of felsic intrusive and extrusive rocks. Areas of complex high-angle faulting such as caldera margins, resurgent domes, horst and grabens, large strike-slip faults with ancillary normal splays all have at least prospects of this type of deposit.

Volcanic activity appears to be relatively important, and at least at Bodie and Hasbrouck Peak (Divide mining district) the volcanic activity was long lived (greater than one to two million years) and complex with development of felsic differentiates (or felsic end of intermediate composition) during parts of the activity.

A sedimentary component of the host rocks appears to be important, particularly volcanoclastic rocks, lake beds, tuffaceous sandstones, or at least some type of rock with a relatively high degree of permeability--such as volcanic tuff breccias.

These deposits are very frequently associated with more typical "epithermal lode" occurrences, and may zone down to this type of deposit, which may or may not have been economically significant. According to Buchanan and Clifton and others (1981, in press) the large hot-spring type zones may well represent the surface expression or "venting" of geothermal systems that produced the lode deposits at deeper levels.

Specific environments where these deposits are found with examples are:

1. Caldera rim fracture zones - Round Mountain
2. Complex volcanic centers, with small plugs, domes and lots of high-angle faulting - Bodie
3. Areas of complex basin and range faulting, with at least some very large-scale displacement - Sulfur
4. Areas of complex basins with volcanic activity penecontemporaneous with faulting - Hasbrouck Peak, Pueblo Viejo (?)

These are very near-surface or surface deposits, and most of them have evidence of surface thermal spring activity. Perhaps the single most important diagnostic feature given some combination of the above observations, is the presence of large areas of intense silicification--several square kilometers anyway.

The one other ubiquitous feature I have seen at these occurrences is evidence of hydrothermal brecciation (hydrofracturing) and minor explosive volcanic activity--such as breccia dikes--rocks with silicified or potassic alteration in an "igneous"-appearing matrix.

I'll get more specific about features in the section following, but first, let me list some of the good signs that serve as signals for this kind of thing at a regional (2 degree or mile to the inch) scale that one might become aware of on a typical CUSMAP or Wilderness traverse.

Good Things to Look for

- (A) Complex high-angle structures--such as the margin of a caldera, or areas of obvious strike-slip faulting with high-angle splays in areas where there has been volcanic activity, of composition at least as felsic as dacite. Small intrusions are a very good sign--they could be simply thin dikes.
- (B) Complex small basins, filled with lake beds, tuffaceous sediments, local ash flows, moat deposits, where there is evidence of intrusion of this stuff by small plugs of dacite or more felsic composition--the areas of Siebert and Esmeralda Formations around Tonopah (San Antonio Mtn) or the Monte Cristo Mountains come to mind as a model for this. Hasbrouck Peak is found in the former area.
- (C) Areas of complex volcanic centers, with a variety of flow rocks, tuff breccias, perhaps some volcanoclastic sediments and small intrusive phases. This may not be so easily recognizable at 2-degree scale. The discerning of intrusive phases from extrusive flows, particularly when there is a lot of hydrothermal alteration is not so easy. High-angle faulting is usually very obvious in these areas.
- (D) Look for demonstrable signs of thermal spring activity--such as wide zones of silicification--the larger the better. Hot-spring sinter tells you immediately you are near surface or at the surface. Silica cemented fanglomerate, volcanoclastic sediment, ash-flow tuff, etc, may also be indicative. Silicification is one of the most recognizable and best signs.
- (E) Argillic, particularly advanced argillic alteration with presence of alunite (if you can recognize it) and/or sulfur is important. These rocks are frequently punky and leached from acid sulfate vapors. At Sulfur, this zone lies above the zone of silicification where the gold prospect occurs. A very important sign here is zones of silicification, particularly where the rock is brecciated--it represents fluid channels to the surface.
- (F) Zones of stockwork quartz veining, particularly where the veins are thin, discontinuous, and chalcedonic are another good feature when you are wandering around in silicified or argillized rock. In this case, I believe you are maybe a little deeper than the surface hot-spring zone--probably just beneath it. (See the figure for Bodie.)
- (G) Finally, having gotten this far, if you see signs of repeated fracturing, veining, brecciation (such as silicified breccia fragments that contain stringers and veinlets that do not cross into the matrix, and small through-going veinlets that cross both matrix and clasts) then start getting interested. Greyish or bluish veinlets are a very good sign because these colors indicate presence of sulfides. Brecciation usually indicates that hydrothermal processes have repeatedly boiled and broken through a self-sealed system. Evidence is building that boiling is an important control on sulfide deposition and mineralization (e.g. Clifton and others, 1980; Buchanan, in press). In this class are pebble dikes, breccias with angular clasts cemented by silica--sometimes chalcedonic. At Hasbrouck Peak veins of this type occur at depth in the system--and show very little displacement of material.

I think these are main channels for fluid movement. At Bodie, these zones are at the present surface, and I believe are well above the zones of discrete "typical" epithermal veins (see Bodie sketch). The brecciation in these features is hydrothermal, and is due to flashing of the hydrothermal system as fluid vapor pressure builds up to break through a sealed (self-sealed) system.

NOTE: These rocks usually have had (or may still have) a lot of pyrite in them. If oxidized, strong color anomalies result light browns, reds, tans, to very white. They stand out on color photos, and on good days from ridge tops.

Physical and Chemical Setting

Wall rock.--varies considerably. At Sulfur, the host rocks are lake beds, lacustrine sediments, volcanoclastic conglomerates, which overlie an older rhyolitic volcanic sequence. The principle, silicified host rock is a volcanoclastic conglomerate and surface sinter is present. Sedimentary textures are preserved despite intense silicification and pyritization--see figure 1. At Hasbrouck Peak, the host rocks are ash flows, tuffaceous sediments, volcanoclastic sandstones and conglomerates, lake beds and sinter. Again, the principle host rocks are intensely silicified, strongly brecciated, and cut by numerous quartz veinlets. Hydrothermal breccias are present and I believe represent major fluid channels. Small-scale veining was important here, as the veins are higher grade than the "disseminated" mineralization.

At Round Mountain the host rock is chiefly an ash-flow tuff, and mineralization is both disseminated and in veinlets. Hydrothermal brecciation appears to have occurred, and explosive igneous dikes were emplaced. There may have been an early stage of adularia-quartz-gold mineralization, and a later hot-spring stage (Berger and Tingley, 1980) with advanced argillic alteration but the age relations despite K-Ar data are unclear. Early veins have sericitic halos. Alunite veins occur, but mostly in oxidized rock. Zones of silicification are present and may have sealed the system at times. I think Round Mountain is a little deeper than Sulfur and Hasbrouck Peak, and I prefer a single system of early adularia-quartz-gold veining, with sealing due to shallow silicification, followed by hydrofracturing due to flashing. Complex structures gave it a lot of fracture permeability which at several stages allowed the low-grade disseminated and veinlet mineralization. Higher grade values are found in brecciated ore--which I interpret as hydrofractured. I think the alunite is mostly late.

At Bodie, the host rocks are largely dacite flows, small intrusions and tuff breccias. It was mined as a lode deposit--the best values being in large adularia quartz veins of typical epithermal character in K-silicate altered wall rocks. Highly silicified zones occur near the top of the system, mostly in block faulted tuff breccia. In these zones, veins lose through-going definition, become thin (mm to a few cm) and chalcedonic. Bodie is structurally complex, and the figure is a schematic representation of zones of alteration-mineralization based on reconstruction. I have to admit that I missed the significance of the upper part of the system in my early work there in 1968 through 1972, and I emphasize its potential for a "mineral occurrence" of this type is not proven. Just recently, I went back and located what

figure 3 shows as the uppermost exposed zone, where only silicification occurs, with a few hydrothermal breccias. The basic geology and patterns of alteration are well known at Bodie, and it would be a good place to study the relationships between the typical and very shallow epithermal environments.

Field data indicates that a high degree of permeability of the host rocks is required to develop one of these systems. I think we are seeing a very shallow zone in which major veins, which represent channels for fluids constrained in tight wall rocks at depth, lose their definition, and the fluids disperse in and alter permeable lithologies such as conglomerates, tuff breccias, etc. In certain cases, where structure is particularly complex, fracture permeability may develop the necessary conditions, and as the systems evolve, they tend to self seal, and permeability then must be developed by hydrofracturing. I see so many examples of stockwork zones, veinlets, and hydrofracturing in these occurrences that I believe this is a very important indication, and that its absence is a negative sign.

Wall rock alteration.--There is evidence of zoning, and it varies in many of the occurrences. At Sulfur, the silicified zone is underlain by argillic rock, and overlain by an advanced argillic zone. At Bodie, K-silicate (adularia-white mica-quartz) appears to have argillic and/or sericitic alteration beneath it and silicification above it. At Bodie and Hasbrouck, the silicification first becomes obvious in originally very permeable units. Lateral zoning to propylitic alteration occurs at Bodie, and in the K-silicate zone, relict chlorite and epidote suggest an early propylitic stage in the K-silicate zone. At Hasbrouck, the silicified zone is surrounded laterally by first argillic and/or phyllic alteration, and then propylitic alteration. Drill-core data suggests it is also underlain by argillic alteration, and zones of argillic and/or phyllic alteration occur within the silicified areas --frequently around small intrusions (dikes or breccias).

Zonal relations are probably controlled by fluid composition, and strongly influenced by levels of boiling (Buchanan, 1981, in press); however, there is enough variation that no one fluid evolution model will explain all observed features.

In the silicified zones, minor to important adularia occurs with the quartz at Hasbrouck, Sulfur, and Bodie. Detailed alteration phase mineralogy in the shallow zones is yet to be studied carefully.

Ore mineralogy.--In general the ore mineralogy of the gold-rich deposits is simple. Pyrite is the most common sulfide, and gold is usually associated --usually in ways unknown. Pyrite and stibnite have been identified in the silicified zone at Sulfur. Above it in the white breccia, cinnabar and sulfur occur. Berger and Tingley (1980) report pyrite, arsenopyrite (?), fluorite, and occasional sphalerite (?) at Round Mountain. Silver occurs frequently, but the mineralogy of it is not known in the deposits mentioned.

Gangue minerals include quartz, adularia, sericite, kaolinite, alunite and occur in the various alteration zones. In the silicified zone, adularia is frequently associated with hydrothermal quartz, which itself is very commonly chalcedonic. Detailed assemblage studies are yet to be done.

Fluid inclusions.--There is no data yet from these deposits. However, most of the epithermal vein deposits studied in the Great Basin have ore fluids dominated by meteoric water, of low salinity, and temperatures between about 150 to 300 centigrade (O'Neil and Silberman, 1974; Taylor, 1974; Nash, 1972). I would expect these deposits to show very similar if not identical fluid characteristics, and perhaps somewhat lower temperatures say 150 to 200 centigrade. Such temperatures have been found at Pueblo Viejo, a variant of this type of deposit, but hosted in carbonaceous, marine sediments, and of more complex mineralogy.

This is an area of great ignorance, even greater than the rest of the above.

The importance of boiling in these deposits must be great, as evidenced by all the hydrofracturing. At what depths boiling takes place, and to what extent it controls the actual zones of mineralization are vital questions. These could be answered by some detailed studies of available drill material and surface and underground areas in the deposits I have mentioned.

Chemical environments and geochemistry.--The environment of deposition is believed to be hot springs or geothermal systems. Trace elements present in the altered zones--best developed where the silicified rock is not totally leached by later sulfotatic alteration in anomalous quantities are:

As, Sb, Hg, Tl, Au, and Ag--sometimes F, Sn, Mo as reported by Berger and Tingley at Round Mountain. The degree of anomaly is variable, and some examples for the deposits (or occurrences) are listed in the table. There is considerable variation between deposits, for example more Ag and Sb at Sulfur relative to Hasbrouck. Berger and Tingley (1980) suggest ranges of these values that become interesting at Round Mountain. These are:

As	300 to 800 ppm
Hg	500 to 800 ppb
Sb	20 to 50 ppm
Tl	1 to 300 ppm (particularly strong in hydrothermal breccias).

I would emphasize that anomalous levels would have to be determined at each occurrence. I don't believe a basic minimum figure exists that could be specified as an "indicator" amount.

These occurrences truly have disseminated mineralization, but the table illustrates that the veins and veinlets tend to be much higher on average in Au and Ag than the wall rocks, and presence of veinlets, and stockworks is a good sign for improving grade. I don't have data for Round Mountain, but much of the early ore was hydrothermal breccia veins and the grades are reported to be nearly an ounce per ton--not bad if there is enough of it.

I believe sampling should be done in bulk to integrate the effects of disseminations and veinlets. For study, veins and disseminated mineralization should be sampled separately.

SELECTED TRACE ELEMENT DATA FROM GRAB SAMPLES
AT SEVERAL "HOT SPRING" GOLD DEPOSITS

Sample	Rock Type	Au	Hg	ppm As	Sb	Ag
Hasbrouck						
THH 25	Silicified sediment	N(.02)	5.0	800	10	2
THH 6	Sericitic sediment	0.15	0.06	L(10)	N(10)	1.5
THH 15	Silicified Hydrothermal breccia	1.0	2.0	80	6	70
H 1	Silicified sinter	.05	.35	80	3	NA
H2	Igneous breccia	.75	.75	20	L(1)	NA
H3	Vein in silicified rock	4.0	G(10)	40	8	NA
Sulfur						
S-1	Alunite vein in silicified rock	L(.05)	0.20	60	300	3
S-1A	Alunite quartz vein	3.0	0.28	10	1	3000
S-4	Alunite vein	L(.05)	2.9	80	46	7
S-2	Silicified pyrite sediment	0.50	G(10)	100	36	5
S-3	Silicified pyrite sediment	0.20	3.0	120	20	15
S-6	Silicified sediment	1.5	G(10)	120	1700	0.5
Bodie--Zone III						
857P2B	Silicified dacite	.04	0.18	20	90	1.2
P2A	Silicified dacite	N(.02)	0.30	20	20	.60
P3A	Silicified dacite	.04	0.40	50	20	.40
P3B	Silicified dacite	.04	0.40	50	20	.40
856P67B	Silicified dacite	.04	.65	80	35	1.0
P67A	Quartz vein	1.80	4.0	10	3.0	14
856068A	Chalcedonic quartz vein	3.7	0.22	10	6.0	63
068B	Silicified dacite breccia	0.1	0.22	80	8.0	12
856069B	Dacite with quartz stringers	12.0	5.5	40	10	110
069C	Chalcedonic quartz veins	4.4	0.9	20	4.0	40
069A	Silicified dacite	N(.02)	0.05	10	30	1.6
069D	Silicified dacite	N(.02)	0.45	80	15	.6
Bodie Zone IV						
857P6A	Silicified dacite	N(.02)	.08	200	15	.8
P6B	Silicified breccia	.02	.70	100	20	2.0
857 07	Silicified dacite	N(.02)	.18	10	20	.20
85708B	silicified breccia	N(.02)	.11	20	8	.20
P8	Argillic breccia	N(.02)	.10	15	15	.20
857P9A	Argillic breccia	N(.02)	.20	150	20	.4
P9B	Silicified breccia	.3	.22	150	15	.6

Ag--by six-step semiquantitative spectrographic

Hg--Instrumentation

Au, Sb--Atomic absorption (Au by MIBK extraction)

As--Colorimetric Analysis

Analyses by B.O.E.R. curtesy of R. M. O'Leary and R. F. Hansen.

Ages

The deposits are young. Most of these occurrences in the western United States, I believe, will be Tertiary, perhaps mid-Tertiary and younger. Because they are so near surface, it is unlikely that very old ones--pre-Mesozoic (?) will be preserved from erosion.

Summary:

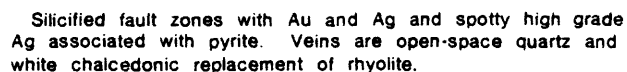
- Sulfur - age of mineralization about 2 m.y. based on ages of alunite from hypogene and supergene veins, no ages on wall rocks or post-ore unite.
- Hasbrouck - age of mineralization about 16 m.y., based on K-Ar ages of sericite and adularia from alteration zones (Silberman and others, 1979). Host rocks are early to middle Miocene, and mineralization occurred during extensive extrusive and intrusive volcanic activity in the immediate area (Bonham and Garside, 1979; Silberman and others, 1979).
- Bodie - age of mineralization from adularia in gold-adularia-quartz veins is 7.1 to 8.2 m.y., with hydrothermal alteration actually starting about 8.6 m.y. ago. Hydrothermal activity started late in a volcanic episode at Bodie that occurred between 9.5 and 8.0 m.y.--dispersion of ages in the hydrothermal system is real, and gives a minimum estimate of its total lifetime. I believe the shallow zones formed above the dated vein deposits (Silberman and others, 1972) at the same time.
- Round Mountain - Questionable. Host rock ash-flow tuff has been dated at about about 26 m.y., and adularia from early quartz-adularia-gold veins gives an age of about 25 m.y. (Silberman and others, 1975). Alunite ages from veins that cut altered, mineralized rocks are about 10 m.y. Berger and Tingley (1980, written commun.) believe this alunite is primary and is related to the major, low-grade hot-spring system. I believe on the other hand that the alunite is late-supergene. Additional K-Ar work on other hypogene alteration phases in the system, also come out at 25 m.y.

The results are suggestive of alteration-mineralization closely related in time to local phases of volcanic activity, and are similar to general conclusions drawn on timing of epithermal vein deposits of this nature (Silberman and others, 1976).

Geophysics

My ignorance is total. Some work done using remote sensing, particular enhanced IR photography by Ashley and others (19) may be useful in finding advanced argillic zones in arid to semi-arid areas.

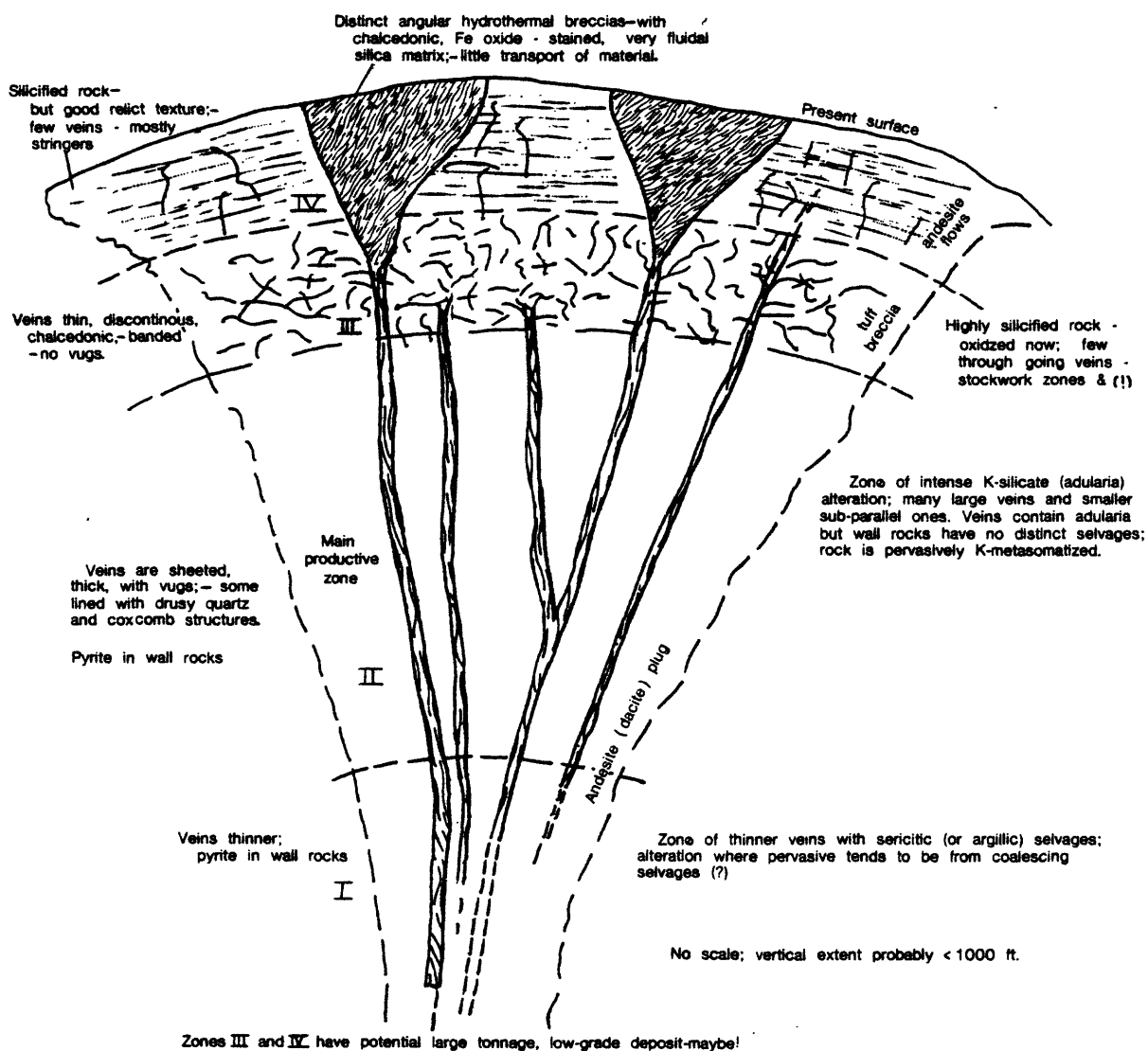
Area is complexly and repetitively faulted. Surface sinter is present just north of the mineralized area.



Late-stage evolution of hydrothermal system to vapour-dominated phase results in deposition of alunite veins cutting silicified Camel Conglomerate-2 my. ago. Some Ag in alunite.

Schematic and idealized cross section of what is left of the geothermal system at Bodie, Ca. Sinter at surface removed by erosion. Much modified from mapping by Chesterman and Gray (in press) and unpublished work of M.L. Silberman, F.J. Kleinhampl, C.W. Chesterman and C.H. Gray Jr. (1970-1980).

(Zones III and IV not actually in contact; - reconstructed from very faulted section.)



Grade and Distribution of Grade

These deposits are large and low grade. Round Mountain has a reported >40 million tons of .06 07/ton Au (B. R. Berger, written commun., 1980). Hasbrouck has an average grade of 0.06 Au and 1.3 Ag (oz/ton) (Bonham and Garside, 1979). Tonnage has not been estimated, but the silicified zone where the metals reside, is more than 300 meters thick, and alteration covers an area of more than a km² (Bonham and Garside, 1979). At Sulfur, the hydrothermally altered area covers over 20 km², and the favorable host rock is nearly 100 meters thick. Grades are low, as indicated on the table, but I do not have much real data. The area is being prospected for large tonnage by Homestake. At Bodie, I do not yet know the thickness of the favorable zone III, but it covers about a square km. However, if the grade is as low as the table suggests, it will not fly. The best potential at Bodie, from the available data, would be to find a stockworks system in zone III.

I mentioned previously that the veins and stringers in this environment tend to be enriched over the disseminated mineralization in the wall rock. Pueblo Viejo, for example, is largely a veinlet, or stockworks deposit, although some mineralization is disseminated. It contains 37 million tons with an average grade of 0.11 Au and 0.57 Ag (oz/ton) (Russell and others, 1981, in press).

Products and Byproducts

Gold and silver. Perhaps mercury and alunite if a use can be found for that. The Russians use alunite for aluminum, and it was mined at Sulfur for that purpose in World War I.

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OCCURRENCE MODEL FOR ENARGITE-GOLD DEPOSITS

By
R. P. Ashley

Enargite-gold deposits are found associated with major volcanic piles, especially those dominated by intermediate calc-alkalic volcanic rocks, throughout the world. Calc-alkalic volcanic rocks occur in several tectonic settings; the deposits occur in all these settings, but are most common in island arcs and back-arc spreading areas. There are two particularly intriguing aspects of these deposits. First, they are always associated with areas of acid-sulfate hydrothermal alteration. Large acid-sulfate areas comprised of argillic and locally advanced argillic rocks occur in all the major accumulations of calc-alkalic volcanic rocks in the western United States, so that much prospective ground may be encountered on Federal lands to be assessed. Second, they occur, again accompanied by acid-sulfate alteration, above and peripheral to some porphyry copper deposits in several of the major porphyry copper provinces of the world. Thus enargite-gold deposits may be shallow-level indicators of deeper porphyry systems, as well as potentially significant gold and copper sources.

The following occurrence model is based mainly on features of four districts: Goldfield, Nevada; Summitville, Colorado; Pyramid, Nevada; and Chinkuashih, Taiwan. Other examples include Bor, Yugoslavia; Kasuga and Akeshi, Kyushu, Japan; Lepanto, Phillipines; El Indio, Chile; Red Mountain district, south of Ouray, Colorado; and Peavine-Wedekind districts, Nevada. Relatively large deposits of this type may contain 1×10^6 to 5×10^6 oz gold and/or 3×10^5 to 1×10^6 tons of copper metal. Most deposits have a high gold-silver ratio ($>1:3$), but a few are relatively silver-rich. Good examples of enargite-gold deposits or enargite occurrences demonstrated to be associated with porphyry copper systems include Cananea, Mexico (Colorado Pipe); El Salvador, Chile (upper levels); and Red Mountain, Arizona.

Host rocks for enargite-gold deposits are usually intermediate volcanic rocks, most commonly rhyodacites, less commonly trachyandesites or quartz latites, and least commonly rhyolites. Sedimentary sequences, usually volcanic-bearing clastics, may also be hosts. Interestingly, intermediate volcanic rocks are always found in the vicinity of these deposits even in districts where most of the ore bodies are in sedimentary rocks. These intermediate volcanics are always porphyritic, and often strikingly so, with a varied assemblage of large and abundant phenocrysts. In the few districts where extensive geochronologic studies have been carried out, the intermediate rocks closely associated spatially with the deposits include units closely associated temporally with hydrothermal alteration and ore deposition. One or more volcanic units usually show intrusive relations, or both intrusive and extrusive relations, to surrounding rocks, indicating that porphyritic domes and flow-dome complexes are typical sites for the acid hydrothermal systems that produce enargite-gold deposits. Most if not all known deposits are of Cenozoic age.

Associated hydrothermal alteration is predominantly argillic. Quartz-montmorillonite is the most common assemblage; it has been documented in many districts, and may be present in every district. Quartz-kaolinite, quartz-kaolinite-K mica, and quartz-mixed layer illite-montmorillonite are other common assemblages. The argillic zone contains advanced argillic zones with

various assemblages that surround the former feeder conduits for the hydrothermal solutions. Assemblage include quartz-alunite + kaolinite, quartz-alunite-native sulfur, quartz-diaspore, quartz-pyrophyllite-diaspore, quartz-alunite-pyrophyllite-diaspore, and quartz-alunite-sericite. Advanced argillic zones within individual districts may display only a few or all of the above assemblages; usually two or three are typical. Which ones develop depends upon intensity of leaching (H^+ supply), total sulfur concentration, and concentration of alkalis (K^+ , Na^+) in the hydrothermal solutions. A titanium oxide phase, either anatase or rutile, is present in any rock that had an appreciable titanium content before alteration. The most intense leaching results in vuggy masses of quartz with minor rutile. Pyrite is ubiquitous in the argillic and advanced argillic zones, usually relatively abundant in rocks that were originally relatively mafic, and scarce in rocks that were originally silicic. Oxidation of this pyrite at the surface produces outcrops with gaudy yellow, brown, orange, or red limonite stains (note the association of deposits with geographic features named "Red Mountain"). Relict textures may be subtle but are common, attesting to the fact that this alteration is largely a replacement process. Propylitized rocks are found peripheral to the argillized rocks in every district, but mineral assemblages vary a great deal both within and between districts. The argillic-advanced argillic alteration of some districts is surrounded by large tracts of strongly propylitized volcanic rocks, whereas in other districts propylitization is restricted to patchy occurrences around the outer edges of the argillic zone.

Ore bodies are always located in or adjacent to advanced argillic zones. Low-grade ores with pyrite as the only obvious sulfide mineral appear merely to be mineralized advanced argillic rock. High-grade ores (>1 oz/ton Au and/or $>1\%$ Cu), however, always fill open-space breccias or fractures formed by breakage of advanced argillic rocks (usually relatively quartz-rich, hard, "silicified" varieties) after alteration was mostly or entirely complete. At Summitville, ore minerals fill voids formed by complete acid leaching of feldspar phenocrysts. In some cases the high-grade ore bodies are formed in post-alteration fault breccias, but in most cases they have very irregular crudely pipe-like or tabular forms not obviously related to any post alteration faulting or jointing. The advanced argillic zones enclosing the ore bodies, however, are often obviously developed along highly permeable structural features such as faults, or stratigraphic features such as coarse clastic or volcanoclastic beds, flow breccias, or lithologic contacts. The mechanism responsible for this late-stage brecciation that is apparently often important in providing the open space necessary for the sulfosalt-rich enargite-bearing high grade ores is still something of a mystery. The latest thought is that the alteration process, through choking of conduits by silica deposition and later boiling, may locally lead to a hydrofracturing stage that produces these breccias. District-wide structural and stratigraphic control varies in detail from district to district, although at least a few large through-going faults are present in every case. Original rock type appears to influence alteration patterns only through permeability, not compositional control, and has no significant influence on localization of ore.

Ore mineralogy is dominated by sulfosalts, including enargite-luzonite series minerals, tetrahedrite-tennantite series minerals, and in some cases silver sulfosalts, and characterized by enargite and luzonite. Pyrite is ubiquitous. Other important minerals vary from deposit to deposit, and

include bismuthinite, native gold, and tellurides. Chalcopyrite is common but minor. Late stage marcasite occurs in some deposits. Galena, sphalerite, and wurtzite are minor and sporadic, but in some districts become more consistently present and locally abundant at the outer edges of productive areas, suggesting a tendency toward district-wide zoning of base metals. The most abundant gangue mineral in ore-mineral breccia fillings is quartz, which forms combs as opposed to the fine-grained mosaics that typify the advanced argillic wall rocks. In addition, barite, alunite, or kaolinite may be important gangue minerals in breccia fillings. However, the ore-filled breccias or fractures are often so intricately interspersed with wall rock on a fine scale that whatever minerals comprise the advanced argillic host rocks must also be considered gangue minerals.

Quantitative fluid inclusion data on hydrothermal alteration phases and quartz contemporaneous with ore minerals are sparse, and material usable for quantitative measurements is typically scarce. The limited information available indicates that the fluids responsible for the acid alteration had generally low, perhaps moderate salinity, and boiling occurred commonly. No data are available on fluids present during the ore-forming stage. Temperatures range from less than 200°C to over 300°C. The common appearance of pyrophyllite accompanied by diaspore indicates that temperatures during hydrothermal alteration exceeded 270-300°C in many systems. Since ore deposition always occurs late in the evolution of these hydrothermal systems, prevailing temperatures may well be less than 270°C during ore formation.

Stable isotope data are also limited. Sulfur is often apparently from a magmatic source, but if a source of sedimentary sulfur was encountered at depth by the hydrothermal fluids, sulfide sulfur may be dominantly from this sedimentary source. Hypogene alunite is moderately to strongly enriched in S^{34} relative to pyrite in advanced argillic rocks. Oxygen and deuterium data indicate that these systems are meteoric-water dominated, as is the case for other epithermal deposits.

Exploration geochemistry utilizing rock samples often does not produce results satisfactory for locating specific drilling targets, especially in the relatively high-gold, low-copper occurrences, because copper and other base metals are leached at the surface and redistributed during oxidation of the abundant pyrite, and precious metals do not form extensive hypogene halos surrounding the ore bodies. However, altered areas that are locally mineralized may have sporadic anomalous amounts of Au, Ag, As, Sb, Pb, Bi, Hg, and possibly Te, Se, or Mo in advanced argillic rocks. Stream sediments analyzed by the semiquantitative spectrographic technique are most likely to show anomalous Ag, Pb, Bi, Ba, and possibly Mo above lower detection limits. Soils may show Ag, Pb, and Bi, but are less likely to show Ba or Mo. The most favorable fractions will vary with prevailing climatic and terrain conditions.

Geophysics has not contributed much to finding ore bodies of this type as far as I know, but much work done by private companies is not published. Detailed magnetic surveys are locally useful in determining the extent of argillic plus advanced argillic rocks under cover and down dip. Electrical methods of various types (resistivity and IP) are capable of detecting variations in character of sulfide mineralization in these areas, but unpredictable variations in abundance of clay and the ubiquitous pyrite make interpretation of results very difficult. Other methods (AFMAG, VLF) have been employed, at least in Nevada areas, but I do not know the results.

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MODEL FOR HYDROTHERMAL ALUNITE DEPOSITS

(Potentially exploitable as aluminum ore with potassium sulfate and sulfuric acid byproducts)

By
R. B. Hall

Regional Setting

Large-tonnage hydrothermal alunite deposits, potentially exploitable as nonbauxite aluminum ore, are found in volcanic terranes characteristically composed of rhyolitic to andesitic ignimbrites, ashflow tuffs and related pyroclastics, flows, and hypabyssal feeder intrusives. Tertiary volcanic fields in Utah, Nevada, Arizona, New Mexico, and Colorado contain the most important deposits recognized so far in the U.S. Similar volcanic terranes of various geologic ages elsewhere in the world also contain significant alunite resources.

Deposit Characteristics

Alunite $\text{KAl}_3(\text{SO}_4)_2(\text{OH})_6$ is found both in hypogene veins and in metasomatic replacements at, or not far from, volcanic vents where rising strongly acidic volcanogenic fluids can attack and alter volcanic parent rocks (see Genesis section). Veins as exemplified by those on Alunite Ridge near Marysville, Piute County, Utah, may be several meters wide and several hundreds of meters long, commonly sinuous in trend, with marked pinching and swelling. They are coarsely crystalline and high grade, but due to their small volumes, constitute a very limited resource.

Replacement deposits are lower grade than veins but constitute the principal resource (even though presently subeconomic) of alunite, both in the U.S. and worldwide. A characteristic zoning pattern generally is present (see accompanying sketch): (1) central silica-rich core or cap-zone (90% SiO_2), commonly chertlike or opaline, in some cases with pores or cavities filled with native sulfur; (2) quartz-alunite zone surrounding or flanking and commonly underlying the silica zone, and consisting of finely crystalline quartz and alunite, with sparser iron and titanium oxides. Alunite content may be 30 percent or greater so that this zone constitutes the "ore" of a potentially commercial alunite deposit; (3) argillic zone, composed of microquartz, kaolinite or dickite, alunite, and Fe-Ti oxides. Sericite, diaspore, pyrophyllite (more rarely zunyite) are common accessory alteration minerals. Sericite or illite ("hydromica") tends to be dominant over kaolinite at the outer or more distal part of the argillic zone, which is a reversal of the phyllic-argillic arrangement that has been observed in typical porphyry copper alteration patterns at depth. Montmorillonite, mixed-layer clays, and chlorite also tends to be more abundant toward the outer margin of the argillic zone as kaolinite and alunite become more sparse; (4) propylitic zone--a relatively mildly altered zone, dull greenish-gray, containing an alteration suite consisting of epidote, chlorite, pyrite, calcite, and zeolites; alunite is absent. Propylitic zones are broad, deep, and pervasive, and may extend beneath the volcanic superstructures down to the level of underlying porphyry copper intrusive stocks (accompanying sketch).

Ideal zoning, described above, is rarely observed in nature; enclaves of one zone commonly occur in another and boundaries are vague and gradational, drawn arbitrarily, based on mineral composition of numerous samples as determined by X-ray diffractometry. It is virtually impossible to map alteration-zone boundaries based on visual observation.

Outcrop Characteristics

Replacement alunite deposits commonly are topographically high, on hilltops or ridge crests, because of the dominance of erosion-resisting compact microcrystalline quartz. The rocks are bleached to an off-white or very light gray, usually with appreciable iron-oxide mottling and staining (hence names like Red Mountain, Calico Peak, etc.). Pronounced yellow or orange tints commonly indicate jarosite or natrojarosite. The fine-grained altered rocks may appear massive and structureless from a distance, but at closer range a layering and a tuffaceous, brecciated, or porphyritic texture may be discernible.

Genesis

Alunite-bearing replacements have been formed hypogenically by acidic hydrothermal solutions and solfataric gases. Soluble Ca, Mg, Na, and K are leached, releasing amorphous silica which recrystallizes into fine-grained quartz or opaline cristobalite (silica-phase is T-controlled although, given time, cristobalite can "cure" into microquartz). Alunite crystallizes more or less simultaneously with the neoformed silica, as judged from texture observable in thin section. Metasomatic volume-for-volume replacement may take place in such a way that original rock texture can be remarkably well preserved in spite of profound change in chemical and mineral composition. Silica is the dominant phase, leading Soviet geologists to apply the term secondary quartzite to these rocks. Part of the silica is residual from leaching of soluble elements but part also has been introduced by SiO₂-rich solutions rising through the volcanic edifice. The "quartzites" are deutero-genic (as recognized, quite properly, by the prefixed adjective, "secondary"), having been originally effusive volcanic or hypabyssal intrusive rock before silicification and alunitization, the alteration having taken place during the late solfataric stage of a volcanic episode.

Alteration is controlled by texture, permeability, and composition of the original rock, the chemistry of the altering fluids, temperature, pressure, rate and continuity of flow, duration of the hydrothermal episode, and structures, including vents, joints, faults, and open fissures. The chemical system is dynamic as the fluids cool and become less acid migrating outward from a central channel and continuously interacting with the rock. Alteration-mineral assemblages in the various zones reflect the stability fields of the constituent minerals, as elucidated by Hemley and others (1969).

Sulfuric acid in the system is derived from volcanogenic H₂S oxidizing near the surface where boiling and exposure to atmospheric oxygen can take place above the water table. Small amounts of primary magmatic water may be involved, but isotope studies in recent years have demonstrated that the bulk of the water in the system is deeply circulating meteoric water, upsurging in a convection cell driven by heat from underlying magma or a still-hot intrusive body.

Volcanic terranes, and particularly calderas, are favorable for formation of large replacement-type alunite-rich bodies because they have essential attributes, including susceptible rocks, an underlying magma chamber, ring fractures and faults which provide channels for hypogene fluids, and a source of sulfur.

Prospecting Techniques

Any bleached iron-stained area in a volcanic setting may contain alunite. It is not easy to identify alunite-bearing rock by visual examination alone. A simple test using pH paper strips to measure acidity of water condensed on the sides of a test tube in which the powdered sample has been strongly heated can be useful. The most reliable method, which is both convenient and semiquantitative, is powder X-ray diffractometry.

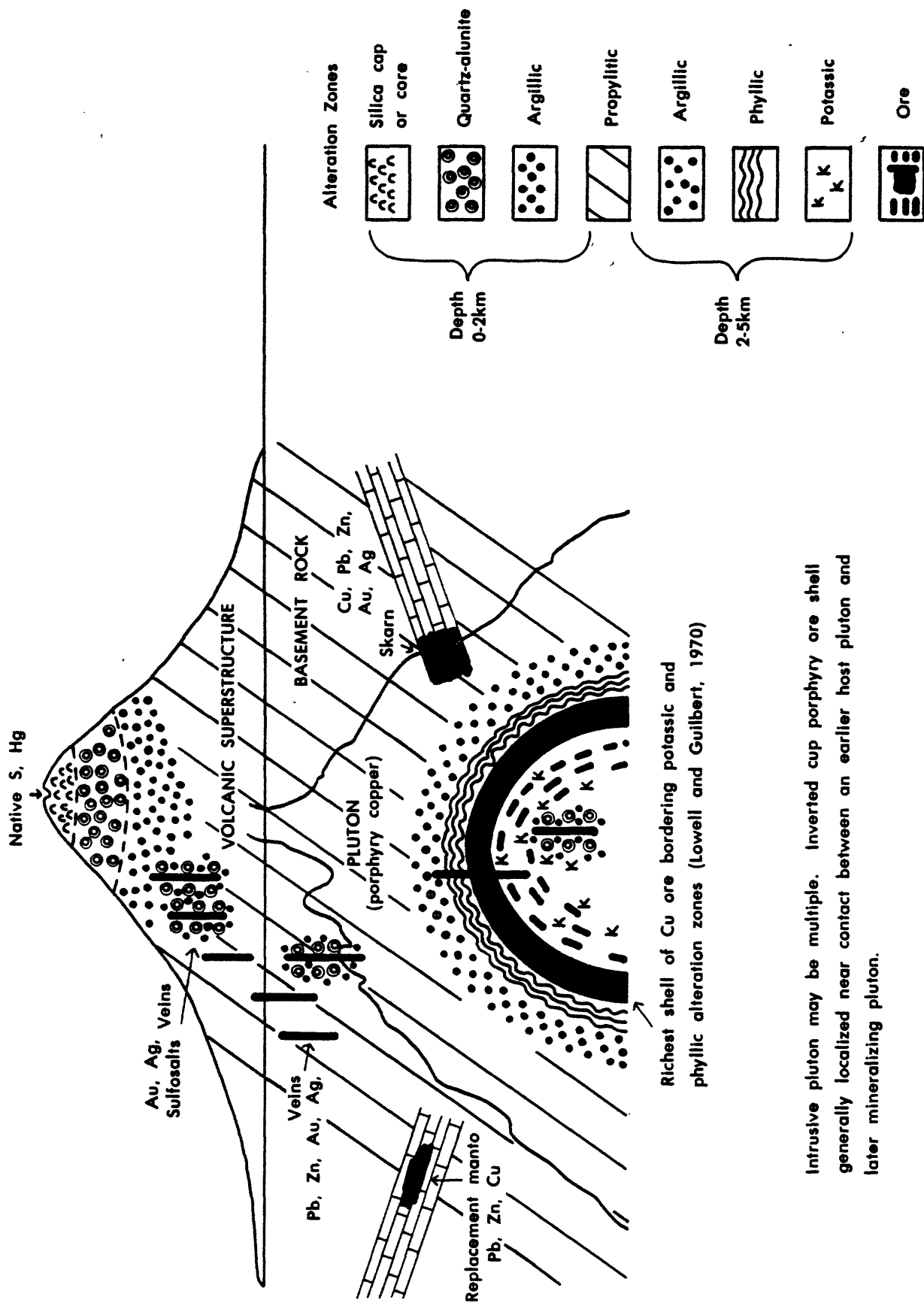
Geologists of Earth Sciences, Inc., Golden, Colo., have successfully located alunitized ground by observing bleached zones ("color anomalies") from aircraft flying over volcanic terranes. By this means, targets are readily identified for ground follow-up.

Ongoing refinements and experiments by the U.S. Geological Survey, the Jet Propulsion Laboratory, and other agencies, using the visible and near-infrared part of the electromagnetic spectrum, offer hope that eventually alunite-bearing ground can be identified directly from high-flying aircraft and from satellites.

Economics

The traditional use of alunite, especially the purer form found in veins, as a raw material for making potash alum and aluminum sulfate has not been practiced since early in the present century. Thus, alunite has fallen into near-total disuse as an industrial mineral. Alunite and alunitic rock served briefly as an emergency source of potassium sulfate fertilizer during the First World War. By the time of the Second World War alunite was being considered as a possible ore of aluminum (with K_2SO_4 byproduct). Although considerable technological advancements were achieved, the peacetime economics were decidedly unfavorable. However, by the mid-1960's the Soviet Union, motivated by a policy of self-sufficiency in raw materials, had established an alumina-from-alunite plant in Azerbaijan, the first commercial-scale operation of its kind in the world. This development, coupled with the recognition in 1970 of large deposits of alunitic rock in southwest Utah by geologists of Earth Sciences, Inc., revived interest in alunite as a potential ore of aluminum in the United States and in other bauxite-deficient countries.

A deposit should hold at least 90 million metric tons of rock containing at least 30 percent alunite in order to be considered potentially exploitable as a nonbauxite ore of aluminum. The economic disadvantage inherent in the low alumina-tenor in 30-percent-alunite rock (only 11 percent Al_2O_3 compared to 45-50 percent Al_2O_3 in most bauxites) is offset to a considerable extent by recovery of K_2SO_4 fertilizer and H_2SO_4 . Value of the acid is enhanced by reacting with phosphate rock to make phosphatic fertilizers. It is important to realize that alunite "ore" should average at least 30 percent alunite, with microcrystalline quartz as the principal gangue mineral. If caustic-soluble silica such as cristobalite or phyllosilicate minerals like clays and mica are



Intrusive pluton may be multiple. Inverted cup porphyry ore shell generally localized near contact between an earlier host pluton and later mineralizing pluton.

present in more than minor amounts, the material cannot be used economically because these breakdown in the caustic leach, resulting in intolerably high loss of caustic soda and alumina. Microquartz is a benign gangue, not soluble in the modified Bayer process currently favored for treatment of alunitic rock.

Relation of Alunite to Hypogene Ore Deposits

Following F. L. Ransome's observation of alunite associated with gold ores at Goldfield, Nevada (Ransome, 1907, 1909), many additional examples have been reported of the association of alunite with metalliferous deposits. Only a few are mentioned here. Alunite is associated with polymetallic deposits in the Summitville district, Rio Grande County, Colorado. The huge deposit of alunitized quartz latite porphyry at Red Mountain near Lake City in Hinsdale County, Colorado, is flanked on the north and east by base- and precious-metal deposits, especially along Henson Creek. Extensive alunitization and alunite veins in the volcanic complex at the Marysville district, Piute and Sevier Counties, Utah, appear to have a genetic relation to ore deposits there; similar associations are known in the East Tintic district, Juab County, and the Frisco district, Beaver County. Further example of alunite association include: "opalite" mercury deposits in Nevada; lead-silver ore at Flathead mine, Montana; porphyry copper systems in Arizona, New Mexico, Chile and Argentina; numerous deposits of various types in the Soviet Union reported by Kashkai (1970).

Alunite indicates a sulfur-rich system and so, indirectly at least, is evidence of environments not far away that are favorable for formation of sulfides and sulfosalts. Alunite occurring in a pervasively altered volcanic or subvolcanic regime may be interpreted as a "flag" marking a favorable exploration target. Andy Wallace (1979) cites altered areas in western Nevada as possible "signatures" of hidden porphyry copper deposits.

No attempt is made here to describe models for all of the various alunite-ore deposit associations. Obviously, no simple or generalized model can fit every case. The accompanying cartoon, adapted liberally but not literally from Sillitoe, Lowell and Guilbert, and others, is a crude first-cut effort to show part of the concept.

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A PROSPECTING MODEL FOR STRATABOUND LEAD-ZINC(-BARITE-FLUORITE) DEPOSITS ("MISSISSIPPI VALLEY-TYPE" DEPOSITS)

By
Walden P. Pratt

In spite of the many features they have in common, Mississippi Valley-type deposits are so varied in detail that it is virtually impossible to describe a single "model" that fits them all. But fools rush in, and here are some generalities, drawn largely from Snyder (1968) and other articles in the Graton-Sales volume, and Pratt (1981), supplemented by personal observations and prejudices. This is a descriptive model, not a genetic one.

Definition

Predominantly galena-sphalerite replacement and vein deposits in shallow-water carbonate host rocks, generally restricted to certain formations but not restricted to specific beds--i.e. stratabound but not stratiform.

Examples

Upper Mississippi Valley district (Wisconsin-Illinois-Iowa), Southeast Missouri Lead district (including Old Lead Belt and Viburnum Trend), Tri-State district (Oklahoma-Kansas-Missouri), Northern Arkansas district, Illinois-Kentucky Fluorspar district, Central Tennessee district, Central Texas deposits (Llano uplift), deep sphalerite occurrences in western Kansas, and Pine Point district, N.W.T.

Regional Setting

Mississippi Valley-type deposits occur in shallow-water marine carbonate rocks of stable platform areas. With the exception of the Illinois-Kentucky and Central Tennessee districts, the principal known deposits and occurrences in North America are in lower to middle Paleozoic (Cambrian-Pennsylvanian) platform deposits where the present Precambrian basement surface is between 200 m above and 1000 m below sea level.

Deposit Characteristics

Most deposits in most districts are replacement bodies, irregular in shape but generally "flat"--i.e. much more extensive parallel to bedding (horizontal) than perpendicular to it (vertical). Individual ore bodies may be as much as 100 feet thick and several thousand feet long. Ore minerals occur as solid masses, disseminations, or vug fillings. Fissure fillings (veins), controlled directly by faults, fractures, or joints, are the dominant form in some districts (Upper Mississippi Valley, Illinois-Kentucky, and Central Tennessee).

Mineralogy is dominantly galena and/or sphalerite, marcasite, and pyrite; in some deposits chalcopyrite, barite, or fluorite are also present and may be abundant. Numerous other sulfides, mostly of Cu, Ni, and/or Co, may also be present in small amounts, belying the notion that the mineralogy is "simple", but they are seldom either abundant or obvious. Common gangue minerals are dolomite, calcite, quartz, and clays.

Host Rocks

Nearly all the known deposits are in carbonates; a few that are in basal sandstones or arkoses are associated with deposits in overlying carbonates. Nearly all carbonate-hosted deposits are in dolomite that appears to be of diagenetic origin and of widespread (regional) extent. One exception to this is the Tri-State district, where the host formation is crinoidal limestone; the ore deposits occur as large, elongated, zoned "islands" of alteration, which include pink dolomite and jasperoid (finely crystalline, "sugary" silica, dark gray or brown to black), with a dolomitic core. Only rarely do ore bodies occur in undolomitized limestone.

Lithologic and Structural Controls

In general, ore deposits occur in carbonate sections with numerous lateral and vertical facies changes, and near a regionally developed limestone/dolomite interface. Immediate host rocks in most cases are fine- to medium-grained dark-gray or dark-brown dolomite. Solution-collapse structures are especially favorable because of their permeability to ore-bearing fluids. Many deposits are in or near digitate algal reef rocks. Pinchouts against basement rocks (exposed or subsurface) are favorable in some areas. Coarsely recrystallized vuggy dolomite ("white-rock facies" of Southeast Missouri usage) is a favorable indicator, but only locally is a favorable host itself. The presence of an impermeable shale caprock, and the absence of an impermeable floor, are favorable factors in some areas.

The importance of structural controls varies widely from one district to another. In general, major structures are not mineralized, but probably have influenced mineralization indirectly. Thus in the Illinois-Kentucky Fluorspar district, many ore bodies are fissure fillings along major fault systems; whereas in the Upper Mississippi Valley district, many ore bodies are fissure fillings on reverse and bedding-plane faults of small displacement. In the Viburnum Trend, visible tectonic structures consist mainly of conjugate shears that are not mineralized but persist through much of the Trend (A. V. Heyl, oral commun., 1981) and may reflect a more significant shear zone in the basement; here, the apparent structural controls were (1) growth faulting that promoted reef development, and (2) strike-slip faulting that fractured the ground widely and prepared it for mineralization.

Empirical Prospecting Guides

We have to assume that in the continental United States, where the favorable host rocks--Paleozoic platform carbonates--occur at the surface, they have been thoroughly prospected at and near the surface; thus, your observations most likely will be limited to drill cores, cuttings, or logs. Make the most of them! In particular look for:

- (1) Dolomite, dark-colored, fine-crystalline, whether diagenetic or hydrothermal (and who can tell?), within a few hundred meters of vertical or lateral transition into limestone.
- (2) Presence of sulfides--galena, sphalerite, pyrite, marcasite, etc.--in soil, outcrop, core, cuttings, or insoluble residues. Collect a suite, indexed as to stratigraphic horizon as well as location, and submit for standard semiquant spec analysis. Get excited about any

analyses that show Ag, Cu, Ni, Co, or Mo notably higher than average for the suite--likewise for Pb or Zn in the iron sulfides. Analyses of HCl-insoluble residues of apparently "barren" carbonate rocks from regionally-spaced drill holes are particularly useful and informative for tracing paths of migration of metal-bearing fluids and outlining broad areas of potentially favorable ground for mineral discovery (see Erickson and others, 1978).

- (3) Alteration products--jasperoid (dark, sugary-grained silica), pink crystalline dolomite.
- (4) Lithologic evidence of solution-collapse breccias--i.e. vuggy brecciated dolomite, angular to subangular fragments, dolomite matrix, not obviously related to faulting.
- (5) Reef or near-reef buildups, whether suggested directly (lithologically) or indirectly (regional interpretation of subsurface lithofacies maps). Here's where it's essential to consult with a carbonate petrologist if one is available.
- (6) Coarse-crystalline, vuggy, white dolomite.
- (7) Any tectonic structures are better than none at all--especially any evidence, surface or subsurface, of a major fault system(s) that extends at least as deep as the target horizon.
- (8) Lithologic or geophysical evidence of small buried Precambrian "knobs" overlapped by carbonate sediments.

If your area has any of the above symptoms, especially #1 in combination with any of the others, run, do not walk, to your local Mississippi Valley specialist, and/or the lead-zinc commodity geologist (Joe Briskey, Menlo Park, 467-2177).

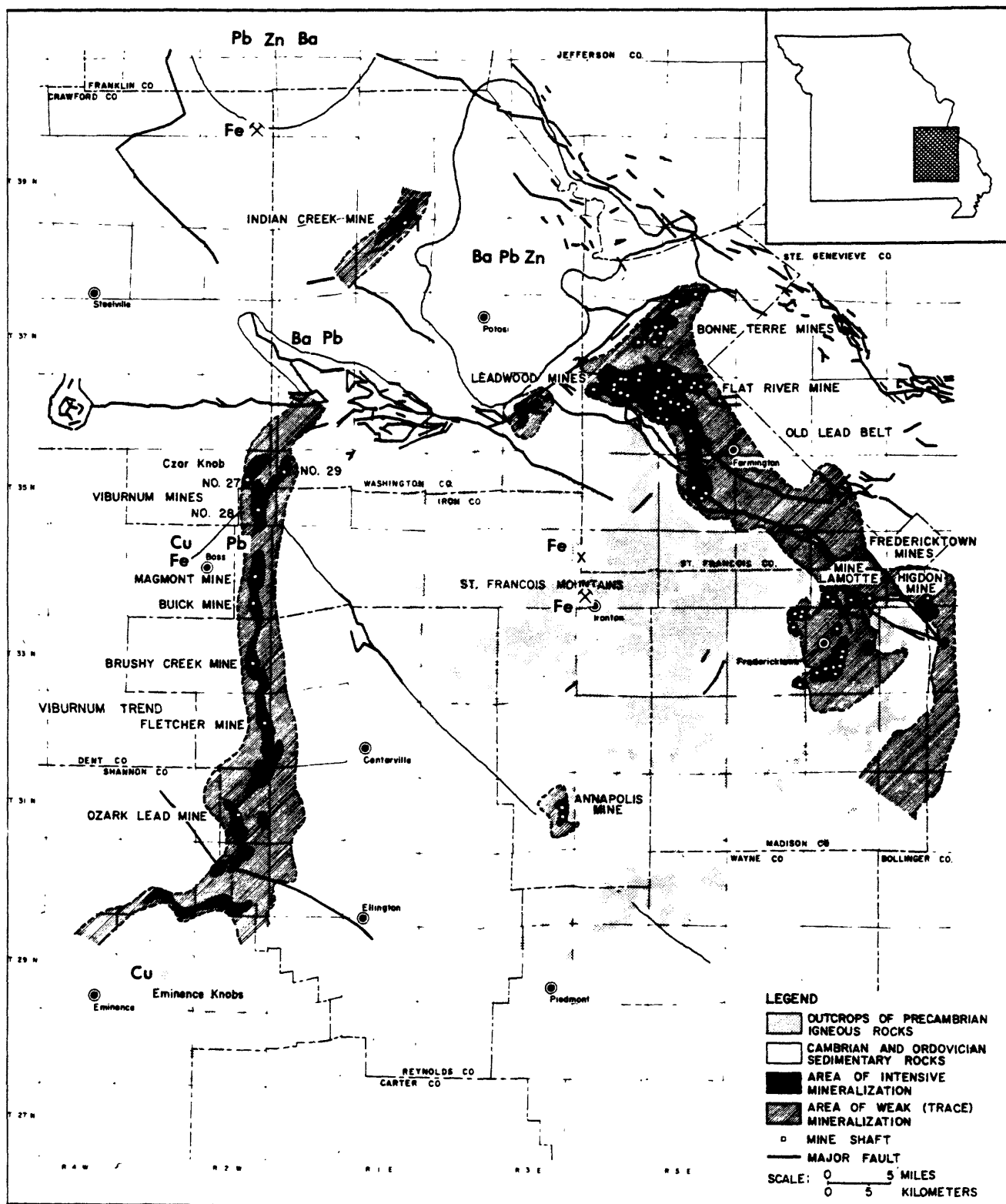
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- Heyl, Upper Mississippi Valley district, p. 431-459

MINERAL DEPOSIT OCCURRENCE MODEL FOR THE VIBURNUM TREND SUBREGION
OF THE SOUTHEAST MISSOURI BASE METAL AND BARITE DISTRICT

By
Allen V. Heyl

- I. The name of the deposit type is the Viburnum Trend lead, zinc, silver, copper, and cobalt deposits, largely in carbonate host rocks.
- II. The model applies to a considerable extent to the entire ring of mineral deposits largely in the dolomite of the Bonneterre Formation and LaMotte Sandstone surrounding the St. Francois Mountains and the Eminence hills. It is most pertinent to the new deposits within and satellitic to the main Viburnum Trend and to the new areas of mineralized rock now being prospected south and east of the St. Francois Mountains. Much, but not all, of the model applies to the "Old Lead Belt", at present idle, north of the St. Francois Mountains. Some applies to the cluster of major deposits near Mine LaMotte, Fredricktown, and Higdon, and also to those at Indian Creek in a separate trend north of the Viburnum Trend. To some extent all the rest of the lead, zinc, barite, copper, and pyrite deposits in the district are interrelated, except most of those in the Precambrian such as the Einstein silver veins, but even here there are exceptions. The Precambrian iron and copper-iron deposits may be related in only one way by providing some of the metals in the Viburnum Trend, the result of remobilization from these older and genetically unrelated deposits by the solutions that produced the lead deposits passing through the iron deposit and extracting some of their metals such as iron, copper, and cobalt, and redepositing them in the lead deposits.
- III. All other main districts in the Mississippi Valley show some geologic features in common with those of the Viburnum Trend. This is especially true structurally, and to some extent mineralogically. Likewise related are some other features in the Upper Mississippi Valley and the old Main Tri-State district of Oklahoma, Missouri, and Kansas. Also, some Viburnum Trend deposit features, such as radiogenic leads in the galenas, largely carbonate wall rocks, giant crystals, ore solution-leaching features, ore in many formations are found in northern Arkansas, the Illinois-Kentucky district, central Tennessee, and central Kentucky districts. Very few of the features of the Viburnum Trend can be extended out of the Mississippi Valley, although the Polish Silesian zinc-lead district has a fair number of comparable features, some can be extended to the Pennines and Derbyshire deposits of England, markedly radiogenic leads in galenas in entire districts are pretty well restricted to Laisvall, Sweden.
- IV. Attributes
 - A. Tectonic/stratigraphic setting
 - Large-scale stratigraphic features
 1. Most deposits known are in carbonate rocks, but deposits in other rocks are known (see a). Most of the Paleozoic rocks lie upon an erosion surface of westward-dipping Precambrian basement.



Map of the southeast Missouri base-metal district (modified from Kisvarsanyi Geza, 1977, fig. 1; in Skinner, B. J., Ed., 1977)

- a. Of the deposits in carbonate rocks, all are in dolomite; none are known in limestone. Former limestones, now dolomites, are favored. Reef fronts are favored. All of the deposits presently mined in the Viburnum Trend are in the Late Cambrian Bonneterre Dolomite, but as other carbonate rock formations are usually blind-bit drilled, little is known of other possibly favorable formations above. But the formations at the surface--Potosi, Eminence, and Roubidoux and Gasconade--are barren except for sparse crystals of galena (Josiah Bridge to Heyl, oral commun., 1944) and very small copper deposits.
- b. Deposits are near the limestone-dolomite interface. The Bonneterre changes to limestone westward and downdip.
- c. Deposits lie beneath a thick cap of nearly impermeable Davis Shale. Several main Mississippi Valley districts lie beneath a thick shale cap. In the Viburnum Trend deposits can occur anywhere in the Bonneterre Formation, but they are more abundant in the upper parts.
- d. Deposits are in a spongy permeable alteration facies known as "brown rock", which is a ferroan dolomite with many small dolomite crystal-lined vugs. Unaltered dolomites in the district are not ferroan.
- e. Most ore deposits are near algal finger reefs, but only 20 percent are within reefs (Ernest Ohle, Paul Gerdemann, John S. Brown, oral commun. to Heyl, 1957-1978).
- f. Best ore is in solution-collapse breccias, or gravity slide (listric fault) breccias (as at the Sweetwater Mine), which cross-cut large parts of the section, including some capping Davis Shale up into the Derby Doe Run Dolomite.
- g. Some of these solution-collapse breccias are pre-ore, or partly pre-ore, but solution continued on a large scale during ore deposition as the result of leaching by the ore solutions.
- h. Stylolites and argillaceous insoluble residues are abundant in the ore zones, sparse or absent outside of them. The residue dark shales are particularly abundant in and near the collapse zones. They are relatively rich in hydrocarbons (Paul Gerdemann, 1978, and Ken Larsen, 1980, oral commun. to Heyl).
- i. Most deposits in the Bonneterre Formation occur where its insoluble residue is greater than 50 percent shale (empirical observation by W. P. Pratt from Thacker and Anderson, 1979, U.S. Geological Survey MF-1002-B). Replacement ore favors these shales.
- j. Most deposits in Bonneterre Formation occur where it is about 200-400 feet thick (empirical observation by W. P. Pratt from Thacker and Anderson, 1979, U.S. Geological Survey MF-1002-A, sheet 2).
- k. Ore is particularly abundant on the northwest side of monadnocks and buried Precambrian ridges.
- l. Impermeable beds within the ore zones, or the much-less-permeable interlocked grains of the "white rock" dolomite facies, which lies nearest the buried hills of the St. Francois Mountains, are notably poor host rocks for large

ore bodies. Ore is lean or absent. The upper beds of the Bonneterre Formation are more favorable for ore than the basal beds or the reef beds. This is opposite of the situation in the Old Lead Belt.

2. In the Viburnum Trend smaller deposits occur (1) in the Bonneterre-LaMotte sandy transition zone; (2) in the LaMotte Sandstone, usually in association with mineralized rocks in the overlying Bonneterre Formation; (3) in dolomitic Davis Shale or other dolomitic shale; (4) in granite boulder talus piles as ore cementing the boulders and cobbles; (5) in wide northerly trending vertical fault and shear zones in the Precambrian directly beneath (or nearly beneath) the overlying main Bonneterre ore bodies. Some of this ore is Precambrian in age, and some is post-Precambrian in age. Elsewhere in the district these granite boulder, sandstone, and other types of ore bodies may make ore bodies containing major commercial tonnages of ore. Copper particularly favors the LaMotte Sandstone and sandy transition ore bodies near the base of the Bonneterre Formation.

Controlling structures and other features

1. Continental scale tectonic features: The Viburnum Trend lies on the western slope of the Ozark Dome near its apex in the central craton of the United States. It lies south of but near the 38th parallel lineament (Heyl, 1972), a subcontinental structural lineament feature. The southeast Missouri district (of which the Viburnum Trend is a part) lies astride this lineament near its intersection with the Ste. Genevieve fault zone, and the Mississippi River Embayment with its New Madrid fault system and Reelfoot Rift plus the associated alkalic post-Precambrian plutons along the fringes of these structures.
2. Local scale tectonostratigraphic features: The age of the Precambrian basement is 1,400 m.y. to 1,270 m.y. with a few younger mafic dikes and aplites. The rocks consist largely of granites of several ages, rhyolitic to slightly more intermediate flows, ash flows and smaller quantities of water-laid tuffs including a little impure iron formation on Pilot Knob in the center of the St. Francois Mountains. The youngest granites are tin granites which form well-rounded plutons in outline, and in some places are bordered by ring dikes and form complexes that may be parts of calderas (Kisvarsanyi, Eva, 1981). Rocks similar to those exposed extend in all directions from the St. Francois Mountains to beyond the limits of the huge 3,000-4,000 square mile mineralized southeast Missouri mineral district. They contain magnetite and hematite deposits of major size and also iron-copper deposits with cobalt and nickel and barium values. Parts of each of the largest deposits have been sponged and leached with huge quantities of iron removed or hematized, and with late (post-Precambrian?) pyrite, marcasite, barite, apatite, calcite, and rare galena (very radiogenic) deposited. There is a possibility that these

deposits acted as source beds for some of the iron and copper in the post-Precambrian deposits. Disseminated copper sulfide deposits are known in the Precambrian tuffs, perhaps related to massive sulfide deposits.

The Precambrian in late stages was strongly faulted in northeast and northwest directions, and to a lesser extent in north and east directions. Renewed movement continued through post-Paleozoic time, and is probably still active today, as indicated by small earthquakes still common in the district today.

Most of the faults and fault zones developed in the mines and at the surface are, undoubtedly, renewed Precambrian faults including those known to have some controlling relationships to the ore of the district. They could also act as channels for the ore fluids, including the downward flow and heating of near-surface waters and brines and perhaps pipelines for deep-seated post-Precambrian fluids to move upward. Any or all are possible and probably available.

The Paleozoic section formerly capped the Precambrian low mountains. Possibly the first Paleozoic age unit to completely cap the Precambrian mountains is the Roubidoux Formation, a sandy dolomite of Lower Ordovician age. The underlying Gasconade Dolomite caps many of the Precambrian St. Francois Mountains, but abuts against some of the higher ones. The lithic facies of the LaMotte, Bonnetterre, and Davis Formations migrate up the sides of the buried hills, so that, for example, Bonnetterre lithology may in reality be Derby-Doerun in age.

3. Structural control: Solution-collapse zones of generally northward direction, but curving from segments of north-eastward to north trend are major structures controlling the ore. They may occur anywhere in the Bonnetterre (and locally in the overlying Davis Shale) but are more abundant above the algal reefs. They range from 20 to 60 feet high and up to 100 to 300 feet wide and contain the richest ore cementing these solution-collapse breccias. Studies in the Magmont and other mines, plus detailed mapping in the Magmont Mine, suggest that these structures are in part pre-mineral, but largely formed during mineralization by the leaching of the active, perhaps slightly acid, ore brines in the most limy beds of the section at the time of the ore deposition. Two initial controls are apparent (1) a shear pair of strike-slip faults of small displacement, which form a zone of northward trend, and probably increased in size and abundance downward, until they reached at least the LaMotte Sandstone; (2) underlying the Viburnum Trend in at least several places is a wide, mineralized, vertical fault and shear zone in the Precambrian. It trends northward and may be the original old system along which slight renewed movement may have occurred at intervals during the Lower Paleozoic to form the shear pair of northward trend in the carbonate rocks above.

These solution-collapse zones extend at intervals for the full length of the Viburnum Trend with some parts barren, too weak, or too lean to mine. They are uncommon or absent in the Old Lead Belt or at Fredricktown. These solution-collapse mines are very similar to the collapse "pitch" zones of the Upper Mississippi Valley district (Heyl and others, 1959, p. 39-66).

The Viburnum Trend is cut off abruptly at its north end by an east-northeast, left-lateral, strike-slip fault. At its south end the trend in the Sweetwater Mine, the south-trending ore body, is abruptly turned to a northwest trend along the northeast side of the Ellington fault. This fault is, in part, a northeast-dipping reverse fault of 100-foot vertical component of displacement, and, in part, a vertical left-lateral, vertical-dipping fault; amount of displacement unknown, the gouge of which is filled with tarry petroleum.

The faults are rarely commercially mineralized, but played an important role in feeding solutions and in ground preparation. Where a fault or collapse zone above it crosses or follows a bar-reef, the ore body is wider, higher, and several times richer in grade in the fractured zone near, along, or above the faults. The control by sedimentary facies, dominant in unfractured or weakly fractured areas is lost in intensely fractured ores. Ground preparation by intense fracturing of indurated rock is one of the most impressive diagnostic epigenetic features.

Low domes near faults in the lower Bonnetterre seem to be centers for copper and copper, cobalt, nickel deposits, which can attain the appearance of massive sulfides. Also, rock slides down from the Ellington fault on the tilted hanging wall side are favorable areas, as are similar areas near Viburnum.

Where basement knobs protrude into the Bonnetterre Formation, ore bodies may occur along the sediment-knob contact, and cement the Precambrian granite talus in all the beds from LaMotte through Bonnetterre. Ore bodies are more abundant on the north and west sides of knobs and reefs. The structures that carry ore may extend unmineralized far beyond the ore bodies without notable change.

4. Stratigraphic/lithologic control: In southeastern Missouri, lead-zinc-barite deposits occur in all formations from shear zones in the Precambrian to the grass roots. At Viburnum the known commercial ore deposits occur in the Bonnetterre Formation. Diagenetic and epigenetic iron sulfide is a common constituent in black shales and gray shaly carbonates.

The most common ore occurrence is at or near the interface of gray and tan dolomites with the best ore in the gray rock, but huge low-grade ore bodies occur in solution-sponged brown rock.

Ore is rare, though present locally in tonnage in the marblelike white dolomite ("white rock"), which is the most abundant facies in the central St. Francois Mountains.

Algal facies account for only 20 percent of the ore is the Viburnum Trend or elsewhere in the district. It is usually too impermeable for ore deposition.

Ore traps may be any feature or situation either sedimentary, solution-leaching, or structural that is juxtaposed upon the two favorable gray and brown lithologic dolomites types.

In most places the ore traps are not completely filled. Vugs and veins of crystals up to giant size are typical. Mineralized rock may closely fit sedimentary structures away from fracture and solution-breccia zones' but the ore may fill open spaces along faults and bedding planes and solution tubes, some of giant size.

The ore bodies are zoned. Copper, nickel, and cobalt are generally low, near main fracture and collapse zones, or capping low domes. Lead is everywhere. Ferroan dolomite is commonly on the east side near the white rock in sponged brown rock with dickite and calcite. Marcasite and pyrite are peripheral both on the sides and near the tops of ore bodies. Quartz and silicified rock commonly are in the same areas. Sphalerite is most abundant in the eastern collapse zones.

Marked changes and discordant features in the height, width, and tenor of ore follow structural features much more commonly than sedimentary features. Open-space filling is abundant as is replacement by ore minerals.

Satellititic ore bodies to the Viburnum Trend have been found and one has been mined (No. 27 mine), and three--(1) the Boss lead ore body; (2) the ore south of the Ellington fault, which trends east-west; (3) the far-east ore body in the Magmont Mine (just found)--are being developed for production.

B. Physical chemical setting

1. Wall rock

- a. Composition: Dolomitized limestone or primary dolomite are preferred. Some ore is in sandstone, shale, siltstone, solution-residue shales and breccias, and in shear and breccia zones in uppermost Precambrian granite and felsic porphyry.
- b. Texture: Ore traps are breccias (fine to coarse), solution-residue shales, relatively coarse dolomite, sponged to high permeability by solution-leaching prior to and during ore deposition, and permeable sandstones. Also, in places, ore is in veins in faults and fractures. Limestone and impermeable dolomite or unfractured primary shale are almost ore-free everywhere.

2. Alteration

- a. The brown ferroan dolomite, so common on the eastern side of the trend, is very probably alteration dolomite. Silicification is locally abundant in the Magmont and Buick Mines, especially replacing fractured rock and as an ore-stage gangue of druse or coarse crystals associated with cubic galena. It is near the top of ore and peripheral. Solution-residue shales are ubiquitous with the ore bodies, and the richest replacement ore is in these black shales. Styolites are everywhere in or near ore, rare or absent elsewhere; they decrease outward. White to light-gray, nonferroan dolomite is present through all the ore stages except the massive early copper ore stage. The crystals range from 1 to 10 mm, and in places are redissolved and redeposited. They are abundant in vugs and present everywhere. Clay mineralogy studies to date are inconclusive but changes from mixed layer illite-chlorite to 2 M muscovite are probably present (from some Old Lead Belt studies) Dickite and Kaolinite were deposited in late ore stages. Crystal overgrowths of adularia on fragments of feldspar only in ore bodies are reported by several company geologists.
- b. Sequential pattern: (1) solution, (2) dolomitization, (3) silicification (early pre-ore and very late with last cubic galena), (4) gray and white dolomites all through ore stages, (5) kaolinite and dickite.
- c. Early premineral stages are fine to medium grained (up to 3 mm). Late during ore stages the alteration minerals are coarse grained (1 mm to 1 cm).

3. Ore mineralogy

- a. Minerals: Very complex for Mississippi Valley deposits; they are moderately complex compared to many Western United States ores.

Ore and gangue minerals in general order of abundance:

galena	digenite
sphalerite	covellite
chalcopryrite	arsenopyrite
dolomite and ferroan	fletcherite
dolomite	adularia
pyrite	pyrrhotite (rare in Buick Mine)
marcasite	magnetite (rare in Buick Mine)
siegenite	millerite
bornite	polydymite
tennantite	microcline
dickite - white	vaesite
crystals in vugs	
kaolinite - white	djurleite
crystals in vugs	
quartz (including	chalcocite
jasperoid)	
calcite	anilite
barite (rare in Magmont)	enargite
bravoite	

- b. Textures: Pre-ore minerals largely are fine grained and replace rock. Ore minerals range from coarse to very coarse (i.e., galena crystals 0.5 meters across are not rare). In fact, crystals, crystal-filled vugs and veins, and giant crystals are characteristic of the deposits. Early galenas and dolomites may be etched or corroded. Some octahedral galena and dolomite rhombs are totally removed by ressolution. Many substages and overgrowths are abundant. Galena cubes envelop octahedrons. Most earlier cubes are etched or somewhat corroded. Colloform galena, sphalerite, bravoite, pyrite, and marcasite, emphasized by Hagni and Tranczyner as abundant (1977, p. 451), are part of a relatively minor stage near the end of several octahedral galena stages of deposition and prior to cubic galena. Unlike the other Mississippi Valley main districts, octahedral galena was deposited prior to cubic galena.
- c. Chemistry of minerals: The main ore galena is in octahedrons. The more obvious and apparently abundant cubic galena is much less abundant and not the main ore. Galena is relatively pure but contains 30 to 50 ppm Ag and up to 1,000 ppm Sb. No Bi is present. Early black sphalerite contains up to 1 to 2 percent Fe, late sphalerite has less than 1 percent Fe. Sphalerite is cadmium-rich (up to 1 percent near faults but much lower elsewhere). Also, sphalerite contains some indium and gallium but no germanium. However, it averages over 300 ppm Ag and more near faults and fault intersections. Chalcopyrite bornite pods contain Ag, As, Bi, Co, Cr, Mo, Ni, Pb, Sb, Sn, Zn, Ge, and in places Au.

Potassium has been added in adularia and in 2 M muscovite (at least in Old Lead Belt). Work has not been completed here. Hydrocarbons are abundant in black shales, some fluid inclusions, and as tarry masses in some faults. Djurleite veinlets have Mn, Ag, Ni, and Pb. Ferroan dolomite contains some manganese. Thallium is present in the copper-rich ores as well as indium. The siegenite series of minerals have a ratio of 40 percent Co to 60 percent Ni, and thus the ores contain more nickel than cobalt. There is enough of these elements in the Viburnum ores to make a major valuable by-product, and recovery and metallurgical efforts are now in progress. Southeast Missouri, including Viburnum, is a major potential cobalt source. The silver in the sphalerite is in the lattice, probably the result of double substitution of some other element.

4. Fluid inclusions: C. G. Cunningham and I are started on a careful research project on this problem. The absence of nonopaques except quartz, sphalerite (almost all very fine grained, except the very latest), dolomite (most probable useful mineral), and calcite (almost entirely post-sulfides). None of the sphalerites (Ed Roedder, 1977, p. 475-477) measured were from the main ore, but were peripheral to the ore. They were coarse grained, brown, and probably very late. As

expected, they show low temperatures on the heating stage at homogenization (101° to 120°C). He did find a very few primary inclusions in the 148° to 162°C range, but these were minimum measurements. Freezing measurements showed very saline brines with salinities between 20 and 25 percent total salts in most samples. Of interest is that sphalerite from a vein in Precambrian rock in the Fletcher Mine showed a much more dilute brine (more like magmatic hydrothermal solutions), which froze between 2.5° and 3.6° celsius. Some galena from this body is radiogenic as shown by lead isotope measurements. Other galena is Precambrian from the same body by similar measurements on other samples. Skip Cunningham and I collected and measured the homogenization temperatures in 1976 on some of the coarse quartz crystals in a huge solution tube encrusted by and encrusting late cubic galena. The homogenization temperatures of the primary inclusions were low--between 110° and 117°C. However, since this was the only place in the Magmont Mine where white platy barite crystals sparsely encrusted the quartz, we suggest that meteoric fluids were brought down through the collapsed Davis Shale in the major collapse breccia zone just east of the tube and parallel to it, so that relatively low temperatures were to be expected.

5. The ore is preserved almost everywhere without weathering or oxidation, just as it was deposited. The Davis Shale has acted as a near perfect impermeable blanket cap. The rocks away from ore are almost unaltered. Near ore they are hydrothermally (hot solution) altered. The present water is meteoric even below sea level and all the brines except those in the fluid inclusions have been flushed. This flushing is typical of all major Mississippi Valley districts. The several stages of ore and major changes from copper to lead-zinc, octahedral to cubic galena through several stages, and multiple etching and corrosion periods all point to a long period of repeated ore depositions, leachings, fluid pH changes from slightly acid to neutral. The huge concentrations of metal alone suggest a long period of multistage ore deposition, unlike that in the Upper Mississippi Valley district. The lead isotope data (see below) support this other data.
6. Chemistry known today reflects the action of three fluids: (1) concentrated heated basin brines, (2) cool meteoric waters, and (3) a magmatic contribution, probably small, but which contributed heat and some of the more oddball elements in the ores. The magmatic contribution was either straight up through the fractures from intermediate or mafic plutons deeply buried in the crest of the Precambrian of the St. Francois Mountain dome. These still unfound intrusions are of perhaps Pennsylvanian-Permian age. Another possibility is that heated fluids using the same fracture system net, were derived from the several alkalic intrusions (partly mafic from their high magnetic signature) which were emplaced during this same period in the west side of the nearby Mississippi River Embayment along the Reelfoot Rift in the New Madrid fault system. These

rocks have the petrology expected to provide copper, gallium, molybdenum, cobalt, nickel, thallium, silver, etc. that occur with the lead and zinc. Most of the lead and zinc probably were provided by the basin brines.

7. I think this has been covered under mineralogy except for the exceptional studies of Erickson and others (MF-1004-A and 1004-B). Spectrographic and chemical analysis of whole-rock and insoluble-residue samples from 62 regionally spaced "barren" drill holes in the Rolla, Mo., 2° quadrangle indicate that insoluble residues are a useful and informative geochemical sample medium in a carbonate environment. The distribution of drill holes that contain the largest amounts of Pb, Zn, Cu, Ni, Co, Mo, and Ag in insoluble-residue samples of apparently metal-barren carbonate rocks outlines the known mineralized trends, follows the limestone-dolomite interface in the ore-hosting Bonnetterre Formation, and favors proximity to subsurface Precambrian "highs". The distribution also suggests that the trends can be projected to form an irregular band of mineralized ground that encircles the St. Francois Mountains.
8. Isotopic signatures: Isotopic and geochemical data place significant constraints on models of ore genesis (Heyl, Landis, Zartman, 1974, p. 992-1006). Lead in galena in the Viburnum Trend (as in all major Mississippi Valley lead-zinc-bearing districts) is appreciably enriched in the radiogenic isotopes of lead, as compared to the lead in galenas in the underlying Precambrian, which are nonradiogenic. The Viburnum Trend has a distinctive lead isotope pattern (i.e., early octahedral galenas are less radiogenic than late cubic galenas). Lead isotopes, however, from peridotite outcrops and drill cores from two Avon diatremes of Devonian age are radiogenic, not as much as at Viburnum, but similar to the nearby Mine LaMotte-Fredricktown district lead in galena. These galenas have trace-element signatures very similar to the Viburnum galenas. Also, the paragenesis of this area on the east side of the St. Francois Mountains has a sequence of deposition very similar to that in the Viburnum Trend. Galena in a narrow zone around one Avon diatreme is also radiogenic, but it has somewhat different ratios from that in the whole igneous rock (Bruce Doe, 1980 written commun.). The wall rock galena also falls within the isotopic range of the galenas of the nearby Avon, Mine LaMotte, and Fredricktown deposits. Thus some nearby alkalic igneous rocks contain markedly radiogenic leads as well as the ore galenas.

The sulfur isotope ($8^{34}\delta S$) ratios in the Buick Mine done by Sverjensky and Rye (oral commun. by Daniel Rye, 1978) range from +4.3 through +20.6. As the sulfur isotopes become more plus, the lead isotopes become less radiogenic in a definite correlation (Bruce Doe, written commun. to James Martin, 1978). These data suggest that sedimentary rocks are the main sulfur source.

To my knowledge oxygen and deuterium isotopic data is not available for this district.

Alkalic igneous rocks near Marion, Ky., near Rosiclare, Ill., and in Riley County, Kans., have been analyzed for strontium isotopes (Zartman and others, 1967; Brookins, 1967, p. 235-240). They have strontium isotope ratios that range between 0.7086 and 0.7019, which suggest mantle derivation. Very preliminary data by Samuel Claredhuri (oral commun. to Heyl, 1978) on Viburnum ore-deposit minerals suggest strontium isotope ratios in two groups; one near 0.709 + that could be, in part, mantle derived, and another about 0.713, which is crustal derived.

C. Ages

1. Wall rock: Precambrian into Lower Ordovician with a concentration in Late Cambrian dolomites, sandstones, and shales.
 2. Mineralization: Very uncertain. Paleomagnetic studies by Beales and Wu suggest a Late Pennsylvanian age for the ores (Beales, Frank, and Wu, Y, 1979, AIME abstract, 1980). The trace elements in the ore minerals enclosing the Hellon Farm diatreme, Avon, Mo, indicate a Devonian or post-Devonian age for the deposits (Hall and Heyl, 1968).
 3. Subsequent events: Continued uplift of the St. Francois Mountains and continued fault movement, earthquakes, and erosion; the last is far above the Viburnum Trend deposits which are unaltered and unoxidized.
- D. Geophysical signatures: None is known, but careful gravity work and locally electromagnetic measurements might be feasible. It may be possible to locate the probable basement fault zone that underlies the trend by magnetics.
- E. Grade and distribution of grade: Broadly the ores have about a 4 percent lead, 1 percent zinc, 0.2 percent copper, 33 ppm of silver per ton of ore (about one troy ounce), but the sphalerite averages 10 oz/short T in Ag, and the galena 1 oz/Ton. Chalcopyrite, pyrite, and marcasite also contain silver. Cobalt ranges between 0.01 to low tenths of a percent. Nickel is between 0.02 and 0.7 percent. The ore bodies are zoned. Some zonal patterns are shown and described well in the Viburnum Trend issue of Economic Geology (1977, v. 72, no. 3). It was also discussed above under mineralogy and zonation. During the first decade of mining, ores averaged 8 percent Pb.
- F. Tonnage and distribution with grade: The original ore bodies of the trend totaled a few 100 million tons of commercial grade ore. Cutoff at good prices is 2 percent lead. As mining continues, the grade will very slowly decrease to 2 percent average grade, which was the average grade during the last 4 decades of ore produced from the Old Lead Belt mines. However, the grade there started originally at about 4-5 percent lead and 0.5 percent Zn.

- G. Products: (A) At present major products are: (1) lead (80 percent of U.S. production, (2) zinc (has largest production of any district in U.S.), (3) silver (over 2,000,000 ounces per year, now a major U.S. silver source). (B) Minor: copper--potentially fairly large, but much of it is unmined because of contained cobalt and nickel, which make a brittle copper. It is produced by St. Joe Industries, Amax, and by Cominco-Dresser, usually by shipping to Belgium or Japan. Cobalt: this trend is a major cobalt resource in the U.S., and large parts of some ore bodies are as rich as Blackbird, Ida. Cobalt has been produced in the Viburnum Trend, but it needs major metallurgical recovery research, which is also true of the more abundant nickel. Cadmium, gallium, and indium are minor by-products.

Genesis and use of a model as a guide to ore: The evidence provided above indicates that the main ore fluids were heated saline basin brines, having largely a shallow crustal source for sulfur, zinc, and to a lesser extent lead. Regional disturbances including uplift, faulting, and intrusions during several post-Precambrian periods provided heat, and perhaps some metals such as silver, copper, molybdenum, cobalt, and antimony. These disturbances initiated large convective systems in and around the St. Francois Mountains that could have produced the Mississippi Valley-type deposits. Precambrian iron, copper, and locally cobalt-nickel-bearing deposits could have provided some remobilized metals, as parts of them have been thoroughly sponged and reworked accompanied by deposition of marcasite, pyrite, calcite, barite, and a little zinc and radiogenic galena similar to that in the deposits above in many respects.

Everything known points to a long period of mineralization with many repetitions and solution changes, perhaps 100 million years. Ernest Ohle (oral commun., 1982) thinks a much shorter ore deposition period like 1 to 10 million years is more probable. Meteoric fluids were convected in the last stages (i.e., calcite) of mineral deposition and the district no longer contains any brines except in the fluid inclusions (even below sea level). Ralph Erickson and his associates's studies (MF-1004-A and -B) support strongly a hypothesis long held by Don Brobst and myself that the mineralized zone forms a ring completely surrounding the St. Francois Mountains, and that much of the ore solutions flowed up dip from the surrounding basins through the Bonne Terre and La Motte beds.

If syngenetic protores existed, they are now completely redistributed, even in the limestones, according to Erickson, and the ores were deposited in lithified rock long after the deposition of the sediments.

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STRATABOUND ZN-PB IN MARBLES OF GRENVILLE COMPLEX BALMAT-EDWARDS, NEW YORK

By
C. E. Brown

Regional Setting

Zn-Pb ores (sphalerite and galena) are rudely stratabound in marbles of the Proterozoic Grenville Complex in the Grenville lowlands. Host marbles are included in a stratigraphic sequence of mainly dolomitic marbles interlayered with tremolite, diopside, serpentine, and/or quartz-rich marbles. Also, in the same metasedimentary sequence is an anhydrite unit and a talc-tremolite unit whose presence suggests an evaporite-producing depositional environment.

This metasedimentary sequence has been folded at least three times. The main structure containing the ore bodies is a northeast-southwest-trending synform overturned to the southeast. The synform is doubly plunging and each end is tightly refolded along northwest-plunging axes. Ore, although roughly stratabound, is now localized along the northwest-plunging axial zones. Rocks are in the upper amphibolite facies of metamorphism.

Ore Mineralogy

Ore bodies are composed mainly of very dark, massive or disseminated sphalerite associated with abundant irregular grains of pyrite. Galena is not abundant and in some ore bodies of the district it is rare. Galena at Edwards is too scarce to recover, but there it is Ag-bearing. At Balmat it is locally abundant, but contains little Ag. Sphalerite contains recoverable Hg in ppm range in the sphalerite lattice.

Deposit Characteristics

Ore is in irregular lenses and thick slabs within certain marble zones and along the axial parts of plunging refolds. Mineral-bearing marble units are stratigraphically close to a talc-tremolite and an anhydrite unit. Ore-bearing marbles commonly are serpentine-rich. (Serpentine is altered from Ca-Mg silicates.) Erosional remnants of late Cambrian sandstone locally overlie the ore-bearing Proterozoic rocks. Chalcopyrite and tennantite occur rarely. Ratio of ore minerals varies between ore bodies, but type of minerals present are similar in all deposits.

Locally, supergene mineralization is associated with a late alteration event related to weathering on the Pre-Late Cambrian surface. Alteration processes apparently continued after sandstone was in place, and produced much hematite with associated willemite, a late iron-poor sphalerite, ilvaite, grossularite, barite, and chalcopyrite.

Outcropping ore is characterized by an orange-brown limonite and cream-colored smithsonite after sphalerite. Ore outcroppings are rare, being buried by glacial deposits at most places. Unmineralized marble units form numerous outcrops and make geologic mapping for ore-controlling structures possible.

Genesis

Syngenetic or diagenetic deposition of metals in Proterozoic time with or in siliceous, magnesium-rich, carbonate sediment in an evaporitic environment. Later tectonic deformation and regional high-grade metamorphism caused recrystallization and migration of sulfides within host strata and along pressure gradients to axial parts of tight refolds.

Prospecting Techniques

1. Locate sequences of marble that include much diopside-tremolite and serpentine-bearing marbles.
2. Do structural mapping to locate tight refolds, followed by geochemical sampling of soils in vicinity of folds. Valley flats containing thick deposits of peaty muck and lacustrine clays do not indicate geochemistry of directly underlying rock. Perhaps trace elements in the peat might reflect mineralization present in drainage basin.
3. Spectrographic analysis of soil samples for base metals and analysis for mercury.
4. Drill for axial parts of folds in anomalous metal-bearing area.
5. Geophysical techniques: none known to be effective, as yet.

Economics

Edwards and Balmat mines have produced about 25 million tons of 10-percent-zinc ore. A newly discovered ore body (northeast of the old district) proved 2-million tons of 20-percent ore in one season of drilling. Many millions of tons of zinc-rich ore reserves are in the Balmat ore bodies. Zinc is the principal commodity recovered. Lead runs less than 1 to 10 zinc. Minor silver and mercury is recovered at the smelter.

Ore bodies are being mined from surface to more than 3000 feet below the surface. Little change in ore attributable to depth.

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MODEL OF CENTRAL PENNSYLVANIA LEAD-ZINC MINERALIZATION

By
Stephen S. Howe

The lead-zinc occurrences in central Pennsylvania are compared in table 1 with 22 other lead-zinc deposits in North America, Europe, and Australia that have been described as Mississippi Valley-type lead-zinc deposits or as having characteristics similar to Mississippi Valley-type deposits. The Central Pennsylvania deposits occur in both clastic and carbonate host rocks that have been strongly deformed. This setting differs from that of many Mississippi Valley-type deposits, but it is certainly not unique. However, more striking is the similarity between the Central Pennsylvania deposits and many other Mississippi Valley-type deposits with regard to mineralogy, paragenesis, temperature of mineralization, and chemical and isotopic composition of the mineralizing fluid. The occurrences in central Pennsylvania are dominated by sphalerite, galena, pyrite, barite, dolomite, calcite, and quartz, as are the other deposits, and even the more unusual minerals such as arsenopyrite, chalcopryite, jordanite, celestite, and gypsum have been found at other deposits. Like the Central Pennsylvania occurrences, many of the other deposits have parageneses defined by nearly monomineralic stages, and in some the stages are separated by tectonic episodes. Although the temperature of mineralization of the occurrences in central Pennsylvania was slightly higher than that of most of the other deposits, the salinities of the fluids depositing sulfides were identical. Even the decrease in salinity during nonsulfide deposition has been recorded from many other deposits. The oxygen and sulfur isotopic compositions measured for the minerals and calculated for the fluids are also very similar. Only the nonradiogenic lead isotopic characteristics of the Central Pennsylvania occurrences are different from many of the other deposits, but here too deposits are known, in the Appalachians and at Pine Point, with similarly nonradiogenic leads¹. Therefore, regardless of whether the lead-zinc occurrences in central Pennsylvania are classified as Mississippi Valley-type deposits, it is clear that very similar chemical processes were involved in the formation of the Central Pennsylvania deposits and other Mississippi Valley-type deposits. For this reason, the model for the formation of the deposits in central Pennsylvania presented here may shed light on the formation of more common ore-grade deposits.

Central Pennsylvania

Host rock: Clastic occurrences: sandstones, and minor conglomerates and red beds, of the Lower Silurian Tuscarora Sandstone, and less commonly, the Upper Ordovician Bald Eagle Formation, the Middle Silurian Rose Hill Shale, and the Middle Silurian Bloomsburg Formation; carbonate occurrences: dolostones and lesser limestones of the Upper Cambrian Mines Dolomite, the Lower Ordovician Beekmantown Group (Stonehenge Limestone, Nittany Dolomite, Bellefonte Dolomite), and the Middle Ordovician Loysburg Formation of the Chazy Group.

¹Heyl et al. (1974) define radiogenic lead as having $^{206}\text{Pb}/^{204}\text{Pb}$ greater than 20.0.

Table 1.--Comparison of the Central Pennsylvanian Lead-Zinc Occurrences with Twenty-two Other Mississippi Valley-type Lead-Zinc Deposits¹

Characteristic	Central Pennsylvania	Other Mississippi Valley-type deposits
Host rock lithology	Dolostones and sandstones about equal in abundance; limestones, shales, and redbeds subordinate.	Dolostones dominant in 15 of the 22 deposits, especially in the mid-continental U.S., Appalachians, and western Canada; limestones dominant in 3, in Central Kentucky, Illinois-Kentucky, and Australia; sandstone dominant in 4, in eastern N.Y., Ontario, Wales, and Sweden; shales, redbeds, and minor sandstones in 6 other deposits.
Regional structure	In folded and thrust-faulted sedimentary basin. No evidence of igneous activity.	At least 17 are on the flanks of or in sedimentary basins, 6 of which are strongly disturbed structurally (Appalachians, western Canada, Wales, Sweden); at least 3 in fold and thrust fault belts, in western Canada and Australia. Igneous activity in Australia, but post-mineralization; cryptoexplosion features in Illinois-Kentucky.
Age of mineralization in relation to age of host rock	Mineralization much later than deposition of the host rock.	Dependent on investigator, but at least 12 ore much later than deposition of the host rock.

Table 1.--Continued.

Characteristic	Central Pennsylvania	Other Mississippi Valley-type deposits
Ore character	Veins filling fractures and joints, in tectonic breccias, as disseminations, less commonly as replacement bodies; tectonic breccias dominant, solution collapse breccias very rare.	Replacement bodies and fillings of solution collapse breccias very common, veins that crosscut bedding in 10 deposits (eastern N.Y., Wales, Ontario, Br. Columbia, Appalachians); tectonic or hydraulic breccias in 6 deposits (Friedensville, Pa., Virginia, eastern N.Y., Northern Arkansas, Br. Columbia, Wales; Friedensville and No. Arkansas have more solution collapse breccia).
Mineralogy	Dominated by sphalerite, galena, pyrite, quartz, dolomite, calcite, barite; lesser amounts of arsenopyrite, chalcopyrite, jordanite, celestite, fluorite, gypsum, hemateite; trace amounts of bournonite(?), pyrrhotite, tennantite, IM muscovite.	All deposits dominated by sphalerite, galena, pyrite, dolomite, calcite, barite; lesser amounts of arsenopyrite, enargite, wurtzite, luzonite, bornite, siegenite, bravoite, millerite, jordanite, gratonite, tetrahedrite, quartz, fluorite, celestite, gypsum, anhydrite, strontianite, illite, muscovite, kaolinite, dickite, K-feldspar.
Paragenesis	Stages nearly monomineralic and separated by tectonic disturbances; pyrite and quartz early, sulfides middle, and carbonate and sulfate late.	Stages nearly monomineralic; stages separated by tectonic disturbances in 5 (eastern N.Y., Friedensville, Pa., Central Kentucky, Upper Miss. Valley Tri-State); pyrite, quartz, or dolomite early, sulfides middle, calcite late.

Table 1.--Continued.

Characteristic	Central Pennsylvania	Other Mississippi Valley-type deposits
Temperature of mineralizing fluid	Quartz; 190°+60°C; barite-celestite-dolomite-calcite-fluorite: ~170°+60°C, but highly variable; sphalerite: 170°+60°C.	Early gangue and sphalerite: 120°+40°C, sphalerite in Upper Miss. Valley up to 220°C, gangue in Br. Columbia and Australia >250°C; late gangue: 60°+20°C.
Salinity of mineralizing fluid	Quartz, most of barite-dolomite-calcite-fluorite, and sphalerite: 24-25 wt % NaCl equiv.; some barite, carbonate, and especially celestite down to 1 wt % NaCl equiv.	Most early gangue and sphalerite: 18-27 wt % NaCl equiv.; some late calcite down to 0 wt % NaCl equiv.
Alteration	Silicification, dolomitization.	Dolomitization, silicification, and recrystallization virtually ubiquitous; bleaching in 4 (Virginia, Central Tennessee, East Tenn., Friedensburg).
Oxygen isotopic composition of the mineralizing fluid	Quartz: $\delta^{18}O = +20.0$ to $+25.7$ ‰; $\delta^{18}O$ of the mineralizing fluid = $+5.1$ to $+11.6$ ‰.	Carbonate gangue: $\delta^{18}O = +12$ to $+26$ ‰; $\delta^{18}O$ of the mineralizing fluids = -5.1 to $+12.8$ ‰. Depletion in $\delta^{18}O$ in host rocks as ore body approached.
Sulfur isotopic composition of the mineralizing fluid	Sulfides: most $\delta^{34}S = +18$ to $+30$ ‰, depletion during late substage of sphalerite deposition; sulfates: $\delta^{34}S = +30$ to $+43$ ‰.	Sulfides: $\delta^{34}S = +8$ to $+30$ ‰, with most greater than $+15$ ‰, late-stage depletion for sulfides in Pine Point, Upper Miss. Valley, Southeast Missouri; Southeast Missouri, Tri-State, Ontario, Australia have sulfide $\delta^{34}S$ values as low as -14 ‰, Silesia as high as $+67$ ‰; sulfates: $+5$ to $+36$ ‰.

Table 1.--Continued.

Characteristic	Central Pennsylvania	Other Mississippi Valley-type deposits
Lead isotopic composition	Very slightly radiogenic, but not anomalous, $^{206}\text{Pb}/^{204}\text{Pb} = 18.61$	For mid-continental U.S. deposits, lead is anomalously radiogenic, with $^{206}\text{Pb}/^{204}\text{Pb}$ greater than 20.0. The deposit in Sweden also has values above 20.0; 7 have values below 20.0 (Appalachians, Central Kentucky, Central Tennessee); Pine Point and Silesia have values between 18.0 and 18.5; Ontario has values between 18.0 and 33.0.

¹Mississippi Valley-type lead-zinc deposits referred to in Table 1:

Shawangunk area, Wurtsboro, New York	Northeast British Columbia
Friedensville, Pennsylvania	Pine Point, Northwest Territories
Austinville - Ivanhoe, Virginia	Cornwallis, Northwest Territories
East Tennessee, particularly Mascot-Jefferson City area	Baffin Island, Northwest Territories
Thunder Bay, Ontario	Central Wales
Western New York - Southern Ontario	Laisvall, Sweden
Central Kentucky	Silesia - Cracow, Poland
Illinois - Kentucky	Mount Black, Australia
Upper Mississippi Valley, Wisconsin - Illinois	
Old Lead Belt and Viburnum Trend, Southeast Missouri	
Northern Arkansas	
Tri-State, Missouri, Kansas, and Oklahoma	
Southwest Alberta - Southeast British Columbia, particularly Oldman River area	

Regional structure: In Valley and Ridge province of the Appalachians. Asymmetrical anticlinoria and synclinoria overturned to the northwest, thrust faults, minor cross-structural reverse and normal faults, cross-structural lineaments.

Ages of mineralization: Late Pennsylvanian-Early Permian (during peak to waning stages of the Alleghanian orogeny).

Local structural control: Tectonic breccia, veins, joints perpendicular to folded bedding; associated with thrust faults, cross-structural faults, lineaments.

Ore character: Fracture- and breccia-fillings, disseminations, minor replacement bodies; sphalerite banded.

Epigenetic mineralogy: Pyrite, sphalerite, galena, arsenopyrite, chalcopyrite, jordanite, pyrrhotite, bournonite (?); quartz, dolomite, calcite, barite, celestite, fluorite, gypsum, hematite.

Paragenesis: Pyrite+arsenopyrite+pyrrhotite; brecciation; quartz; fracturing; barite+dolomite+calcite+celestite+hematite+fluorite+gypsum; minor fracturing and stylolitization; sphalerite; fracturing; chalcopyrite+galena+jordanite+bournonite (?); warping; dolomite+calcite+barite+quartz.

Temperature: Quartz: 88° to >400°C, most 160°+60°C; barite, dolomite, calcite, celestite, fluorite: very widely scattered between 100° and 370°C, Tregaskis (1979) found temp. of 120° to 160°C for fluorite; sphalerite: 84° to 196°C, most 140°+ 20°C.

Depth of mineralization: Uncertain; possibly 1-2.5 km.

Salinity: Quartz: 21.0-29.2 wt % NaCl equiv.; barite, dolomite, calcite, celestite, fluorite: 1.0-26.8 wt % NaCl equiv.; sphalerite: 23.8-28.8 wt % NaCl equiv.; most inclusions in all minerals have salinities of 24-25 wt % NaCl.

Alteration: Silicification, dolomitization. Epigenetic 1M muscovite found in one area. From silicate and carbonate equilibria calculations, pH between about 4.5 and 5.0.

Redox state: Sphalerite banded. FeS content in sphalerite from Woodbury area = 0.7-1.0 mol %, corresponding to an $a_{S_2} = 10^{-12.5}$ for a pressure-corrected temp. of 200°C.

Hydrogen isotopic composition: ?

Oxygen isotopic composition: Quartz: +20.0 to +25.7 per mil. Calculated $\delta^{18}O$ of water precipitating quartz during stage 2 = +5.1 to +11.6 per mil.

Carbon isotopic composition: ?

Sulfur isotopic composition: Syngenetic-diagenetic pyrite: -10.8 to +5.7 per mil; epigenetic pyrite, sphalerite, galena: +16.4 to +33.6 per mil, with a marked depletion during the late substage of stage 4 sphalerite deposition of +1.2 to +19.0 per mil; barite, celestite, gypsum: +30.0 to +43.2 per mil. $\delta^{34}S$ of H_2S in the fluid between +20 and +30 per mil except during the late substage of stage 4.

Lead isotopic composition: $^{206}Pb/^{204}Pb = 18.61$ (Heyl et al., 1966).

References: Howe (1981), Heyl et al. (1966), Roedder (1967, 1971), Smith (1977), Tregaskis (1979).

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SUMMARY OF THE GENERAL GEOLOGIC CHARACTERISTICS OF SANDSTONE-HOSTED LEAD-ZINC DEPOSITS

By
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Sandstone-hosted lead-zinc deposits are typically "stratabound" and commonly stratiform concentrations mainly of fine- to medium-crystalline galena and subordinate sphalerite deposited in multiple, thin, sheet-like ore bodies contained within continental, terrigenous, and marine arenaceous sedimentary rocks.

Host rocks are mostly quartzitic and arkosic sandstones, conglomerates, grits, and siltstones, and locally include associated phosphorites, limestones, and iron-rich dolomites. Evaporite minerals are usually present nearby, either within or immediately above or below the ore-bearing sequences. Quartz and carbonate are the main cementing agents. Many of the host rocks are the products of piedmont, lagoonal-lacustrine, lagoonal-deltaic, lagoonal-beach, and tidal channel-sand bar sedimentation. Rocks containing known deposits range in age from Proterozoic to Cretaceous, with major ore bodies occurring in Proterozoic, Eocambrian, Pennsylvanian, Triassic, and Cretaceous units.

Mineralization generally consists of fine- to medium-crystalline galena with sporadic smaller amounts of sphalerite, pyrite, barite, and fluorite. Minor, highly variable quantities of chalcopyrite, tetrahedrite-tennantite, chalcocite, freibergite, bournonite, bornite, cerussite, and malachite are also present. Pyrrhotite and magnetite are reported from highly metamorphosed deposits. Quartz and calcite are the usual gangue minerals.

Mineralization commonly occurs as black, regularly distributed subspherical clots from 0.5 to several centimeters in diameter; or as disseminations 0.1 to 1 mm in diameter that are evenly distributed through the rock, or that form irregular patchy concentrations (clouds). Mineralization typically forms more massive ore bodies where localized by sedimentary structures such as normal bedding and crossbedding, paleochannels, liquification structures, and breccias related to intraformational slumping. Ore also accumulates along the margins of impermeable barriers such as shale interbeds. In many places, the transition from disseminated to massive ore occurs where disseminated mineralization progressively coalesces into linear to planar groupings of clots of galena, which are localized along sedimentary structures such as normal bedding and crossbedding. These groupings become progressively larger and more closely spaced and grade into elongate to irregular masses of galena. Ore may occur within or immediately above paleochannels, or less commonly, above paleoridges. In many deposits, ore is closely associated with accumulations of organic matter. Faults, joints, and fractures locally contain substantial quantities of more massive ore.

Mineralization and quartz and carbonate cement fill the interstices between detrital grains, and paragenetic relationships between mineralization and cementation are contradictory in places. Although it is typical for mineralization and cement to coexist without reaction along their mutual boundaries, galena locally replaces the cement, especially when the cement is carbonate. Many clots of sulfide minerals contain 10 to 20 percent galena occurring interstitial to both detrital grains and quartz cement; however,

locally galena is totally surrounded and partially replaced by quartz cement, and may even appear to be disseminated within it. There is a recognizable tendency for galena and quartz cement to be closely associated throughout some deposits.

The finely crystalline, interstitial character of the galena in sandstone lead deposits, combined with surface oxidation of galena to cerussite, make recognition of mineralized outcrops difficult. A useful field geochemical technique for detecting finely crystalline oxidized lead in outcrops involves spraying the freshly broken outcrop with a 5 percent solution of acetic acid (white vinegar), waiting 1 minute, and then spraying the same area with a solution of 5 percent potassium iodide. If cerussite or anglesite are present, a canary-yellow lead iodide precipitate is formed. This test is sensitive to as little as 0.5 percent cerussite, equivalent to about 0.4 percent lead (Jerome, 1950).

Consistent mineralogical zoning in sandstone-hosted lead-zinc deposits is not well documented. In some deposits, zinc increases upward relative to lead, and both metals tend to be mutually exclusive. Whereas, in other deposits, lead and zinc occur together and become more abundant upward. Barium and fluorine, and to some extent silver, are relatively enriched in the lowermost parts of some ore zones. Obvious wallrock alteration has not been recognized in sandstone-hosted lead-zinc deposits; presumably reflecting the relatively nonreactive character of the predominantly siliceous wallrocks, and of the low temperature (<150°C) near neutral (pH-5) Na-Ca-Cl brines from which galena and sphalerite appear to have been precipitated.

Major sandstone-hosted lead-zinc deposits occur as multiple, thin, sheet-like ore bodies localized within clastic sedimentary sequences that may contain sporadic mineralization along more than 1,500 km of strike length. Although the deposits are "stratabound" on a local scale, regionally mineralization transgresses stratigraphic boundaries. Within a given district, most ore zones are separated by intervening weakly mineralized to barren beds at least several meters thick, but in plan view ore zones commonly overlap one another. Vertical variations in ore grade are greater than horizontal changes. Ore zones are generally elongate sheet-like masses 2,000 to 4,000 m long, 50 to 1,500 m wide, and 2 to 30 m thick.

Exploitable ore bodies or closely spaced clusters of ore bodies generally contain from 1 to 80 million metric tons of ore with 3.5 to 5 percent lead, 0.5 to 0.75 percent zinc, and 8 to 80 grams per ton silver. Typical examples include: Laisvall (Richard and others, 1979), Vassbo, and Guttusjo (Christofferson and others, 1979), Sweden; Largentiere, France (Samama, 1976; Michaud, 1980); Bou-Sellam, Morocco (Caia, 1976); and Salmon river, Canada (Hornbrook, 1967; Scott, 1980). The George Lake deposit (Karup-Møller and Brummer, 1970; Sangster and Kirkham, 1974) in Canada appears to be a zinc-rich analogue (5 million tons; Zn=2.65 percent; Pb=0.34 percent).

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BLACK SHALES AS SOURCES OF MINERALS AND FUELS

By

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General Statement

Organic rich shales occur in all ages of sedimentary rocks on all continents and ocean basins. Shales with 2 or more percent organic carbon by weight appear black. Some black shales may have been source rocks for oil and gas by heating due to burial to several thousand meters but others still are thermally immature and are potential sources for hydrocarbons. Black shales often contain larger amounts of certain metals (e.g., V, Mo, U, Zn, Cu, Hg), which have an affinity for organic matter or sulfide, than less organic rich rocks. These metals may have been introduced during syngensis, diagenesis or during subsequent epigenetic or hydrothermal processes. At some places and in some shales, the amount of one or more metals may be large enough to be of economic importance. Metal contents at the lithologic top or bottom of the black shale sequence may be larger than elsewhere in the unit. This feature will not necessarily be uniform either stratigraphically or geographically and sampling must be designed accordingly. Thick sequences (>5 m) of highly organic (>10 percent) shales have most potential value for retorting for production of oil and gas and recovery of metals.

Summary

The geochemical properties of organic-rich and sometimes metal-rich black shales result from the interaction of factors that can be summarized as follows:

1. Organic productivity in the depositional basin.
2. For post-Silurian settings, the influx of terrestrial (allocthonous) organic matter into the depositional basin.
3. Oceanographic characteristics of the basin, including tectonic dtability, depth, temperature, salinity of the water, etc.
4. Flux of metals into the basin from adjacent terrestrial sources, from distant volcanic sources. from intra-basin volcanic sources, and from possible spreading zones.
5. Sedimentation rates of both organic and inorganic particles. Low sedimentation rates favor higher metal and organic contents based on less dilution by clastics.
6. Pre-depositional processes operating on organic matter. Processes mostly are oxidizing and depend on in-transit residence time of organic matter.
7. Depositional processes at or near the sediment-water interface can concentrate metals.
8. Post-depositional processes operating on accumulated organic matter and sediment during early diagenesis. Anerobic sulfate reduction is the principal process, but it is proceded and accompanied by a complex of preparatory processes involving organic matter and followed by processes involving H_2S and derivative compounds. The metal contents of organic matter and sulfide minerals seem to be fixed during this step.
9. Late diagenetic and thermal history. This may be the time of epigenetic or hydrothermal introduction of additional metals. The nature of organic

matter can be changed by generation of liquid hydrocarbons, mobilization of sulfide minerals, and formation of carbonate concretions with largely undetermined effects on the metal content of the rock.

Discussion

Black shales in the geologic column are important for organic and metal enrichment and as source rocks for oil and gas and metal deposits. The metal deposits are of several types: syngenetic, sources for supergene or epigenetic processes, or as local hosts for hydrothermal metals. The shales are also interesting as indicators of past environments that were atypical, but not unusual, and which occur in many ages of rocks and physiographic settings. Geological and geochemical understanding of black shales is at present inadequate. Even classic black shales have not been completely studied in detail using modern tools and ideas, such as isotopic data, concepts of plate tectonics and analyses for biomarker organic compounds.

The following discussion relates to apparent depositional processes, early and late diagenesis and epigenesis, followed by a look at modern analogues with an emphasis on asking questions which, if answered, could further our understanding of black shales. The last section deals with specific examples of types and ages of black shales and methods of sample collection and analysis.

Black shales result from the combination of a variety of depositional and early diagenetic processes. Preservation of sedimentary organic matter is at an optimum within oxygen-depleted water masses such as in anoxic basins, or under open-ocean oxygen-minimum zones where such zones impinge on the continental slope or outer shelf. The amount of organic matter in sediments and its initial degree of preservation, however, is a complex function of the following: productivity in surface water related to nutrient availability; amount and type of terrestrial organic matter input, rate and distance of fall of organic material through the water column to the sediment/water interface and the degree of oxygenation of the water column through which organic matter falls; residence time of the organic matter at the sediment/water interface, which is related to intensity of bioturbation by macrobenthos that generally require O_2 concentration >0.5 ml/L, and rate of sedimentation; rate and duration of bacterial sulfate reduction in pore waters that become anoxic following burial.

Although many of the aforementioned processes have been studied individually, much work remains to allow quantification and prediction of sediment organic matter contents and composition as a function of each parameter. In very general terms, higher productivity of organic matter leads to higher organic matter content in sediment, but the rate and distance of fall through an oxygenated water column is critical to the amount and degree of preservation. Fecal pellets may be a major and efficient transfer mechanism for organic matter from surface waters to sediment. Systematic sediment trap studies of this mode of transport in modern environments would be useful to evaluate this.

Sedimentation rate in various depositional environments can act in opposite ways to either dilute the organic matter flux to sediments, or to enhance preservation of organics by affording rapid burial, isolation from

burrowing, and rapid passage through the sulfate reduction zone in the sediment. Recent studies of some modern environments have shown a good direct correlation between organic matter content and sedimentation rates. Yet we know of very slowly deposited sediments with high organic matter contents in the ancient record. More studies of these relationships are necessary to understand the origin of black shale.

Organic matter

Understanding of the early diagenesis of organic matter, which includes reactions from within the water column to the end of sulfate reduction during burial, is critical to prediction of hydrocarbon source bed potential of different types of black shale and to elucidating the relationship between black shales and economic mineral deposits, such as sedimentary phosphorites, and between black shales and the geochemical cycles of nutrient elements and metals (Vine and Tourtelot, 1970, Leventhal, 1979b). Necessary studies of interaction of phosphate, nitrogen, and metals with organic matter in modern sediments and the subsequent distributional changes of these elements during early diagenesis are lacking.

Further consideration of the value of various organic geochemical and stable isotopic markers for recognition of sources of and degree of preservation of organic matter in modern environments is also crucial to studies of ancient black shales. Pristane/phytane ratios, even/odd hydrocarbon predominance, $\delta^{13}\text{C}$ values, atomic H/C and O/C ratios, pyrolysis (Leventhal, 1981) and many other parameters have been used to evaluate the source (terrestrial vs. marine) and preservation environment (anoxic vs. oxic) for organic matter. Many difficulties exist in the application of these methods to the ancient record, and as yet, many have not been systematically tested in modern diagenetic studies.

As post-shale sedimentation and subsidence continue, temperature and pressure increase and late diagenetic and epigenetic changes occur. In this changing physical environment, both organic and inorganic phases inherited from the depositional and early diagenetic environments are no longer in equilibrium with their surroundings. As a result, recombinations and rearrangements will progressively take place in order to reach more stable phases or configurations. For the inorganics, this means progressive changes in clay mineral suites, recrystallization of carbonates, authigenic formation of quartz, feldspar, etc.

Changes that take place in the organic matter (kerogen) produce a higher degree of ordering, tending towards the graphite structure as the ultimate thermochemical product. To do this, steric hinderances such as nonplanar cycles or carbon side chains, have to be eliminated and oxygen, hydrogen and nitrogen released. This constant adjustment of kerogen to increasing temperature and pressure results in a progressive elimination of functional groups and linkages between molecules. As a result, a wide range of compounds is formed (petroleum) which includes low to medium weight, saturated and aromatic hydrocarbons, CO_2 , H_2O , H_2S , etc. The amounts and chemistries of any hydrocarbons generated are dependent on the composition of the initial organic matter input into the environment, and on any syngenetic-early diagenetic alteration that takes place.

As thermal maturation of the kerogen proceeds, petroleum generation finally decreases and methane becomes the most important product. Unfortunately, as petroleum and methane generation proceed, the chemistries and physical properties of initially different kerogens become similar and quite difficult to distinguish. Detailed organic geochemical research on different types of organic matter at different thermal maturation levels is necessary to understand the original nature of organics in thermally very mature shales.

Metals

The chemistries of any initially organically bound metals will also change as the organic matter matures. These changes and their effects on metals amounts and distributions are at present poorly understood. Epigenetic enrichment of metals (addition of metals from external sources) in organic-rich rocks are probable because: a) the organics act as reducing agents for some metals in solution resulting in a more insoluble form and precipitation; b) these rocks can be a source of reduced sulfur; and c) phosphates and/or siderites associated with some black shales are favorable sites for replacement.

Determining when a metal or metals were introduced into a shale (syngenetic, early diagenetic, or epigenetic) can be difficult. The literature contains a number of examples (Kupferschiefer, Nonesuch shale, the mine at Rammelsberg) where scientific debate between opposing camps has raged for years. The presence of much ambiguous data and lack of recognized critical criteria are the main reasons for such arguments. Nevertheless, the three above examples have been and still are important sources of metals.

Some aspects of the origin and genesis of black shales can be studied by analogy to modern environments and processes. This is most true of the geochemistry of depositional and early diagenetic environments since the geologic settings and later diagenesis either take more time (and are not modern) or the settings are not exactly the same. The modern analogy is also useful for the true syngenetic end member, but less so for early diagenetic addition of elements or, of course, diagenetic or epigenetic mineralization.

Modern analogue

The Black Sea is one well studied modern chemical analogue for black shales, with special attribute that it has an H_2S -bearing water column. H_2S occurs in the water column today only in unusual settings; however, in the geologic past H_2S may have been more widespread in different settings. Interior basins with restricted access to the ocean are good candidates for density stratification where rainfall exceeds evaporation since this will provide a less-dense cap above the more-dense, saline ocean water. Another case is temperature or tropical smaller oceans, these settings are enhanced by restricted north to south circulation which prevents addition of sinking oxygenated polar deep water. A depth of at least 100 meters is probably necessary for stable stratification regimes. Many of these environments should have existed in the past.

Other recent environments include offshore basins, such as off southern California, and off southwest Africa (Walvis Bay), the O₂ minimum type; fjords

in Norway and British Columbia; and shallow seas such as the Baltic, the salinity stratification type (Arthur and Schlanger, 1979).

Recent examination of the Black Sea has shows that some useful geochemical analogies can be used (Leventhal, 1979a). Reinvestigation of the carbon and sulfur contents of Black Sea cores has revealed an interesting effect. A plot of organic carbon vs sulfur shows excess sulfur (positive S intercept) at zero carbon. This is distinct from the origin intercept of modern oxic ocean water sediments (Goldhaber and Kaplan, 1974). The sulfur excess can be interpreted as an indication of sulfate reduction in the water column--hence an H_2S containing water column. It also appears that the slope of the C/S line is related to several factors including availability of Fe, type of organic matter, H_2O salinity, but mostly to layer sedimentation rate as with modern sediments, and thickness of the H_2S - or thinness of the O_2 layer. Thus, by analogy to the modern Black Sea, a large amount can be learned about the presence or absence of H_2S in the water column over an ancient black shale. This H_2S is extremely critical for organic preservation and metal trapping. C and S measurements should be made on unweathered material, preferably from a core.

Another useful analogy is between enriched trace elements and their assemblages. In particular, both enhanced U and Mo contents are associated with higher organic carbon and sulfur contents in the Black Sea. The same behavior is present in Devonian age shales of the Appalachian, Michigan and Illinois basins of the U.S. It is likely however that the metals are related to the organic matter because of the high solubility of Mo-sulfides and the association of U-fission tracks in organic matter but not sulfides in the Devonian shales. A further suggestion is that black shales with enriched Mo and U need not have an H_2S bearing water column, although it happens that the Black Sea does, and probably the U.S. Devonian basins did. The H_2S in the water column should be evident by enhanced enrichment in certain other elements such as perhaps Cu, Pb, and Zn which form sulfides with a low solubility.

Examples

1) The Middle and Upper Pennsylvanian section of the Midcontinent area (Iowa, Nebraska, Missouri, Kansas and Oklahoma) and the Illinois Basin (Illinois, Indiana, and Kentucky) contains at least a dozen thin (0.15 to 1.8 m), very widespread, phosphatic, metal rich black shales. Stratigraphically, these shales occur above coals and are often interbedded with carbonate rocks. According to Heckel (1977), these shales represent deposition at the time of maximum transgression of the seas during the cyclic deposition characteristic of this part of the section. Organic-carbon contents of the shales range from 4.0 to 30 percent and they are enriched in U (as much as 125 ppm), Mo (as much as 700 ppm), V (as much as 3,600 ppm), Ni (as much as 400 ppm), Cr (as much as 1400 ppm), Ag (as much as 18 ppm), and Zn (as much as 15,000 ppm).

Sphalerite has replaced some phosphate nodules in the shales. High zinc contents in shales occur in areas where some coals contain abundant sphalerite (Hatch, 1979). The sphalerite in coals has been interpreted by Hatch, Gluskoter and Lindahl (1976) to be of epigenetic origin. A similar origin for at least part of the Zn in the shales is suggested.

Organic geochemical comparisons of shales and coals show that organic matter in the shales came mostly from the peat swamps (Hatch and Leventhal, 1981).

2) The Middle and Upper Devonian shales of the Appalachian basin are organic-, sulfur- and metal-rich (Leventhal, 1979b). The best known example of these is the Chattanooga Shale of Tennessee which contains as much as 19 percent organic carbon, 8 percent sulfur, 100 ppm U, 200 ppm Mo, 1,300 ppm Zn, 1,000 ppm V, 700 ppm Ni, and 7 ppm Ag. Over wide areas, the Chattanooga is only 10 meters thick, and equivalent thicker units in other parts of the basin are not as rich in organic matter or metals. Based on carbon-sulfur relationships, it seems that this shale was deposited under an H₂S-laden water column similar to the modern Black Sea. Certain units in the section contain organic matter of terrestrial origin, and it is in these units that the uranium and molybdenum concentrations are largest. Samples with marine organic matter contain smaller amounts of U (Leventhal, 1981) but often larger amounts of V or Ni. A phosphate bed at the top of the black shale sequence is enriched in rare earth elements and at some places in U.

3) Sharon Springs Member of the Pierre Shale, Western Interior Region, United States and Canada

The Sharon Springs Member of the Pierre Shale extends from Saskatchewan and Manitoba south to central Kansas and from the general western margin of the central craton of the United States westward into Montana, Wyoming, and Colorado. Throughout this extent, the shale thickens from a few meters on the east to several tens of meters on the west. Organic carbon contents generally are larger than 1 percent, and commonly are 10 percent or larger (Tourtelot, 1964). Selenium, arsenic, uranium and other metals are enriched regionally in the shale, as shown by reconnaissance studies for uranium in South Dakota, Nebraska, Kansas, and Colorado. The unit seems best interpreted as a shelf deposit bordering the central craton. The unit has not been sampled in sufficient detail to identify areas where metal contents are maximum.

Exploration Guide

In order to evaluate the metal and oil and gas producing potential and to learn about the origin of a given black shale, the following kinds of information need to be collected: A) thickness and lateral extent of the black shale unit, B) stratigraphic position of any interval containing phosphate nodules, disseminated, nodular or vein filling sulfides, or volcanic ash or bentonite beds (samples should be collected at five foot intervals or at stratigraphic breaks, whichever is less), C) a scintillometer profile perpendicular to strike, and D) well-documented samples for geochemical analyses. A) is important because metal and organic matter contents may be higher where the section is thinner, a result of less dilution by clastics. B) is important in that nodules and sulfides may indicate local concentrations of metals; U, for example, correlates well with phosphate content in Middle and Upper Pennsylvanian Midcontinent black shales. Ash beds or bentonites may be a source of metals. The scintillometer profile (suggested in C) will show the presence of uranium-rich zones and perhaps zones of highest organic content, which cannot be estimated from color, because it is all black. Contents of other metals (V, Ni, Cr, Mo, Ag, and Zn) often correlate well with uranium content, hence, a scintillometer profile would indicate possible

distribution of these elements. For geochemical analyses, the fresher and less weathered the samples are, the better, particularly for organic geochemical analyses. Core, mine, and drill chip samples are best but seldom are available. The freshest possible samples should be sought. Element analyses for evaluation of both economic potential and geochemical history should include organic carbon, total sulfur, total iron, phosphorus, uranium, vanadium, molybdenum, chromium, nickel, silver, and zinc. The oil and gas potential and the thermal maturation level of the shale can be evaluated from the organic carbon content and a Rock-eval type pyrolysis analysis.

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METALLIFEROUS ORGANIC-RICH PALEOZOIC MARINE STRATA OF THE WESTERN UNITED STATES

By

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Regional settings

Three general depositional settings of metalliferous organic-rich marine strata in the Western United States include: (1) continental-rise (Vinini and Woodruff Formations), (2) continental shelf and foreland basin (Meade Peak Member of Phosphoria Formation), and (3) cratonic-platform embayment (Heath Formation).

General characteristics

Many units within these formations contain >5 weight percent organic carbon and are enriched in certain valuable metals such as vanadium, molybdenum, selenium, nickel, chromium, silver, cobalt, cadmium, or zinc. Where these strata have not been subjected to thermal effects due to deep burial or an external heat source, they are low-grade oil shale.

These metalliferous organic-rich marine strata are collectively called "black shales" because of their very fine grained constituents and the olive-black to brownish-black or very dark brown color of the fresh rock. Typically they are very poorly expressed in natural exposures due to their nonresistant nature, except for those facies which are highly siliceous or cherty. They also tend to weather rapidly, even in relatively young exposures such as roadcuts, landslide scars, bulldozer cuts, and prospect pits. In these cases they alter to lighter shades of gray, buff, and brown. Where they are highly argillaceous and laminated, black fissile shale fragments may be conspicuous in the soil, even in places of relatively deep weathering with good soil development.

Characteristics of selected deposits

Central and northeastern Nevada--Outcrops of metalliferous oil shale in the Ordovician Vinini Formation typically occur as light-gray, fissile-weathering graptolitic shales which are interbedded with brownish-black mudstones and siltstones. Fresh specimens are thinly laminated, and contain dispersed, shiny, black kerogenous graptolite fragments which are about the only components visible with a hand lens. Exposures are generally poor due to the high content of clay minerals.

Devonian Woodruff Formation which hosts the thickest intervals of syngenetic low-grade vanadiferous oil shale in the Western United States occurs as siliceous, dolomitic, and argillaceous mudstone with a significant quartz component. The finely granular nature is not always conspicuous due to the interstitial kerogen. The siliceous or dolomitic mudstones may have some topographic expression due to their somewhat erosion-resistant nature, and this is accentuated where there are also interbedded cherty layers. These strata alter to light-gray colors during earliest stages of weathering, but may acquire buff or light-buff colors where they are more oxidized. Fresh specimens of the highly siliceous facies are olive black and may contain 1-mm-wide discontinuous bluish-white opaline-silica veinlets and black shiny

kerogenous material which occurs as specks or is associated with the silica veinlets. Small clots of bitumen-like material may be present. Incipient alteration may produce a red coating of metaheulandite, or it may occur in clots, voids, or along fracture surfaces. Conodonts, sponge spicules, radiolarians, and spore fragments have been seen with a hand lens in some beds. Most fossils are microscopic and generally not visible in these strata. Sparse iron sulfide may be visible with a hand lens where it occurs along small fractures or veinlets.

The metalliferous dolomitic facies of the Woodruff Formation has distinct bedding due to alternating lithologies from dominantly argillaceous beds to dominantly dolomitic or cherty beds, all of which range from 2 to 20 cm in thickness. The dolomitic beds weather to round edges, whereas the cherty beds weather to sharp edges, and the nonresistant argillaceous beds weather to form recesses. Light-gray colors develop due to oxidation of the organic matter and the cherty beds develop a spongy surface. The pale-brown weathering spongy chert fragments which are highly leached, have a low specific gravity due to their highly porous nature, and occur in residual soils where these strata are weathered. Thin laminations are generally detectable in the dolomitic facies and 1-mm-thick discontinuous layers of pyrite occur parallel to bedding. Oxidation of the pyrite produces thin streaks of iron oxide.

Both the Vinini and the Woodruff Formations are part of the eugeosynclinal assemblage which was folded and faulted during the Antler orogeny.

Meade Peak Member of the Phosphoria Formation in southeastern Idaho and western Wyoming--These metalliferous organic-rich Permian marine strata consist of black dolomitic and argillaceous beds which are 0.2-1 m thick, and are interbedded with pelletal phosphorite, dolomitic and calcareous mudstone and siltstone, and minor dolomite and limestone. Macrofossils are generally absent. Because of the nonresistant nature of the argillaceous organic-rich beds, they are seldom exposed, whereas those which are dolomitic crop out more prominently. Most strata weather gray or buff. The dolomitic beds are commonly pale yellow brown in color due to oxidation of pyrite. Weathering and deep ground-water leaching of these strata have been accelerated due to numerous fractures and faults developed in tectonic transport during Sevier folding and thrusting. Consequently, fresh organic-rich strata are found chiefly in prospect pits, adits, stream banks, and roadcuts.

Heath oil shale of central Montana--These metalliferous Mississippian oil shales occur interbedded with fine-grained calcareous strata which are chiefly limestones, calcareous shales, mudstones, claystones, and siltstones. Most of the associated limestones are dark brown on fresh surfaces and have a petroliferous odor when broken. The metalliferous mudstone and siltstone beds are brownish black and range in thickness from several centimeters to 1.5 meters. The thinly laminated nature of these shales yields gray fissile-weathering shale chips which occur at the surface even where weathering has been extensive enough for soil development. Soil development from weathering of these black shales is generally dark brown, and small fragments of gypsum are commonly present. In some shale beds, 1-cm-thick brachiopod coquina layers are conspicuous, some beds have flattened brachiopods along bedding planes, and others contain no visible fossils. Secondary selenite has grown along some bedding surfaces in the black shales. Although the associated

thicker limestone intervals are generally well exposed, the black shales have a significant clay component and are nonresistant. Stream beds, landslide scars, and roadcuts are about the only places where these black shales are exposed.

Origin

Conditions necessary for low-temperature accumulation of significant metal and oil concentrations in these black shales include: (1) marine basin setting, (2) high content of organic carbon, (3) low content of calcium carbonate, (4) high content of sapropel (mostly marine algae) and low content of detrital land plant material, (5) slow rate of deposition of detritus and (or) chemical precipitates, and (6) anoxic environments of deposition and diagenesis.

Concentrations of metals differ from bed to bed and from area to area, reflecting variations in depositional and chemical conditions. Some of the metals reside in the organic matter whereas others reside in metal-sulfide minerals. Mineralogical and chemical studies of these black shales indicate that most of the metals were derived from seawater and accumulated in kerogen-rich sediments within the O_2 minimum zone.

Prospecting techniques

In the Western United States, metalliferous organic-rich Paleozoic marine "black shales" may be identified by their light-gray fissile-weathering nature and (or) low bulk rock density, except where they are dolomitic. Fresh strata are always fine grained and very dark colored and commonly shiny black specks of hydrocarbon may be visible. Elements such as molybdenum, zinc, and nickel are generally depleted by incipient weathering, whereas vanadium and selenium are enriched upon weathering. A pungent odor commonly can be detected from outcropping vanadiferous and seleniferous shales (e.g., the Gibellini-Bisoni vanadium deposit in Nevada). Botanical prospecting using plants that require certain elements for normal growth has been applied successfully in uranium and vanadium exploration. In Nevada, for example, the 1-m-or-more-high plant "Desert Princessplume" preferentially grows on selenium- and sulfur-bearing colluvium and soil developed from weathering of the vanadiferous and seleniferous Vinini and Woodruff Formations. In areas of moderate relief, such as in central Montana, landslide terrain is developed in the intervals containing black shale, and dark-colored landslide scars are commonly visible from a distance of 1 km or less.

Although it is possible to recognize black shale units in the field that are likely to contain anomalous concentrations of metals and oil, it is necessary to adequately sample the rocks for analysis because the metals and oil generally are not visible in these fine-grained rocks.

COPPER SHALES
By
David A. Lindsey

Introduction

This preliminary model is generalized from my recent observations of three copper shales: the Permian Kupferschiefer in Poland (Oberc and Serkies, 1968; Haranczyk, 1972), the basal Nonesuch Formation (Precambrian) in Michigan (Ensign and others, 1968), and the Permian Flowerpot Formation in Oklahoma (Johnson, 1976) and Texas (Smith, 1974). I am indebted to Franciszek Ekiert of the Polish Geological Institute and his many colleagues, to Kenneth Johnson of the Oklahoma Geological Survey, to Gary Smith of the Texas Bureau of Economic Geology, to Paul Daniels of the Michigan Geological Survey and to Glenn Scott of the Copper Range Company for their guidance in examining these deposits.

Geologic Setting

Copper shales are found in rift basins (Ziegler, 1978; Halls, 1978) and in shallow-marine basins (Smith, 1974) that develop over filled rifts. Rifts under the three copper shales discussed here are intracratonic, but rifts in tectonic belts formed by continental collision (e.g., Mediterranean Sea) are likely settings; also, intracratonic rifts containing or overlain by copper shales may form in response to collision (Kluth and Covey, 1981).

Rifts are filled by thick sequences of coarse alluvial sediments, evaporites, and commonly by hypabyssal and volcanic rocks of mostly basaltic composition. Coarse alluvial deposits in rifts are generally oxidized red and overlain by evaporites. A typical stratigraphic sequence is: (1) conglomerate and sandstone redbeds with interbedded with basaltic flow rocks or sills; (2) thin, organic-rich shale and limestone that is locally the host for copper, and (3) evaporites that follow the expected sequence for evaporation of sea water (limestone/dolomite-anhydrite-halite-sylvite). The typical rift-filling sequence may vary considerably, depending on the relief of the basin floor and surrounding highlands, repetition of tectonism and uplift, extent and duration of connections with the sea, and distance from shoreline. Such factors may account for anomalies in the normal stratigraphic sequence, such as the absence of evaporites and presence of red beds in strata above the Nonesuch copper shales of Michigan.

Characteristics of Ore Deposits

Copper in the Polish Kupferschiefer deposits occurs in organic-rich shale and limestone, and in adjacent limestone (hanging wall) and sandstone (footwall). Shale ore of the Kupferschiefer is organic-rich, but ores from other copper shales typically contain a percent or less organic carbon. Most of the ore mined in the Fore-Sudetic monocline of Poland is from white sandstone immediately below the Kupferschiefer. Although concordant in any one mine face, the deposits in Poland and Michigan transect lithologic boundaries. Copper deposits occur in reduced (gray, black) beds, but are richest near oxidized facies (hematite spots--the Rote Faule of Rentzsch, 1974) of the host beds. The deposits may be zoned vertically and horizontally: chalcocite, bornite, chalcopyrite, galena, sphalerite, and

pyrite from bottom to top and away from the oxidized facies in the Kupferschiefer (Banes and others, 1974; Rentzsch, 1974); native copper, chalcocite, bornite, chalcopyrite, galena-sphalerite, and pyrite from bottom to top at White Pine (Ensign and others, 1968). In the Kupferschiefer, the oxidized facies passes laterally to reduced facies of copper, lead, and finally zinc-rich shale over approximately 10-km distance. Only chalcocite facies are known from the Permian copper deposits of Texas and Oklahoma.

Mine and Outcrop Characteristics

Ore is in shale, limestone, or sandstone, but is near shale or carbonaceous limestone. The organic-rich host rock (shale or limestone) of the Kupferschiefer is usually delicately laminated but without abundant macrofossils except those tolerant of extreme environments. Sulfides (pyrite, chalcocite, chalcopyrite, bornite, galena, and sphalerite) are commonly visible, but most ore values may be in microscopic grains invisible to the eye. Late fracture fillings of chalcocite (underground) and blue and green stains and crusts of copper carbonate (outcrops) are characteristic of copper shales. In sandstone and carbonate ores, sulfides may be visible as patches and spots filling voids and replacing host rock. Nearby oxidized facies of the host shale and organic-rich limestone show conspicuous red spots (Rote Faule of the Kupferschiefer) of iron oxide that may retain microscopic remnants of pyrite and even chalcocite.

Genesis

There are three main theories for the origin of copper shales: (1) syngenetic-early diagenetic, (2) hydrothermal (early or late), and (3) ground-water diagenetic. Variants of the syngenetic theory include (a) accumulation of metal-rich plankton remains on anoxic ocean shelves (Brongersma-Sanders, 1967, for Kupferschiefer), direct precipitation of metals in sediment pore space by concentrated brines trapped in lagoons or barred anoxic basins (Haranczyk, 1972, for Kupferschiefer), and precipitation from copper-rich brines by evaporative pumping on sabkas (Smith, 1974, for Flowerpot Formation). Studies of stable isotope composition of the Kupferschiefer show that C and S are of biogenic origin (Wedepohl, 1971); lead isotopic studies show that these ore deposits are approximately the same age as the host shale. The hydrothermal theory envisions mineralizing fluids rising along faults in the rifted basement, accompanied by precipitation of metals during deposition of organic-rich sediments (Ekiert, 1958, for Kupferschiefer). A variant of the hydrothermal theory has precipitation of copper deposits occurring much later than deposition of host sediments. The ground-water theory involves leaching of copper and other metals during oxidation of clastic sediments to form red beds, and precipitation of metals as such waters pass upward and outward through reducing facies (Ensign and others, 1968, for White Pine; Rydzewski, 1976; Rentzsch, 1974; for Kupferschiefer). Dunham (1964) discusses earlier proposals.

Hydrothermal, ground-water, and some early diagenetic theories require the presence of fine-grained, organic-rich sediment to act as a semi-impermeable chemical barrier to flow of mineralizing fluids and as an acid, reducing chemical environment for precipitation of metal sulfides. Such organic-rich sediments may have an initial syngenetic enrichment of metals and biogenic sulfur, especially as pyrite, that served as nuclei for

mineralization. Such copper sulfide-after-pyrite paragenetic relations are observed to be nearly universal in copper shales. The vertical and horizontal zonation of metal sulfides observed in some copper shales is in accord with the relative solubilities of these compounds (Rentzsch, 1974), and reflects direction of flow of mineralizing fluids and/or chemical gradients in the fluids.

Exploration Techniques

Geologic -- Explore in rift-filling sedimentary sequences that contain red beds and evaporites; look for reduced and/or organic-rich sediments near red beds and examine transitions between the two facies. Check the literature for copper occurrences and note or map their stratigraphic settings. Examine reduced facies for concentrations of organic matter, radioactivity, copper stains, and pyrite; look for red spots in otherwise reduced (gray) limestone and shale; map the distribution of all of these features.

Geochemical -- Sample reduced facies for chemical analysis. Copper, Mo, Pb, V, Zn, and sometimes Ag and U should be present in anomalous concentrations. Construct geochemical maps and profiles of mineralized rock units to delineate metal zones. Transitions from iron to zinc, lead and copper-bearing facies and from oxidized to reduced facies are especially useful in locating areas of greatest mineral potential.

Geophysical -- None known for exploration of frontier areas; seismic methods are used in Poland to trace the Kupferschiefer in the subsurface.

Economics

Large underground mines, each producing more than 1 million tons of >1 pct Cu ore per year, are developed in the Kupferschiefer of Poland and at White Pine, Mich. Copper (<1 pct grade) was produced briefly from the Flowerpot Formation at Creta, Okla. Copper from shales may yield byproduct silver, and the refined copper metal commands premium prices owing to its high Ag content and consequent desirability for special uses. Molybdenum, Pb, U, V, and Zn are among potential byproducts from Polish ores.

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PRELIMINARY CONCEPTS OF A SIMPLE EXISTENCE MODEL FOR LARGE SANDSTONE URANIUM DEPOSITS

By
Warren I. Finch

Introduction

Sandstone uranium deposits undoubtedly have received more study than any other single type of mineral deposit, a safe guess of at least 10,000 man years since 1947. An extensive volume of literature exists describing sandstone deposits, and their environments. They are truly a world-class uranium deposit, for large ones are found on every continent outside the polar regions. Many models of sandstone uranium deposits have been published (Weir, 1952, Fischer, 1970, 1974; Brooks and others, 1978; Mathews and others, 1979; Peterson and Turner-Peterson, 1979; Granger and others, 1980; models by R. I. Rackley and S. S. Adams in Gaschnig, 1980, p. 15-141; Harris and Carrigan, 1980; Adams and Saucier, 1981; Adams and Smith, 1981; Harshman and Adams, 1981; Thamm and others, 1981; Nash and others, 1981; Otton, 1981; Dickinson 1981), and most uranium explorationists have a model in mind when they evaluate or explore a given area. From the extensive knowledge base coupled with my experience and biased view, I have chosen the key attributes that seem essential for the existence of important or large (generally more than 10,000,000 pounds of contained uranium with a value of more than \$250,000,000) economic uranium deposits in sandstone formations. It is these essential attributes that I plan to mold into a simple existence model that follows a series of logical genetic steps or stages one would probably use to model any type of mineral deposit (Finch and others, 1980). I do not plan to present a treatise on sandstone uranium geology, but rather plunge right into model itself.

Model Formula

The geologic favorability for the existence of sandstone uranium deposits can be assessed on the basis of four broad geologic attributes, namely, favorable precursor conditions (P), favorable host rock (H), preparation, commonly alteration, of host rock (A), and an adequate source of uranium (S). If one assumes that all four attributes must be present in the form prescribed as favorable for large economic uranium deposits, a simple equation will express favorability (F):

$$F = P \cdot H \cdot A \cdot S$$

The assumption is made that each factor has equal weight in determining favorability, and the value for each ranges from 0 to 1. Evaluation of each attribute is based on the available data. If hard factual data support the complete presence of a given attribute, full weight of 1 is given that attribute. If, on the other hand, some data indicates less than full development of favorable geologic conditions or some data are lacking or of poor quality in the judgment of the assessor, a value of less than one is assigned that attribute. It should be emphasized that the total absence or unfavorability of one attribute results in zero favorability, and that if two or more factors have low values the resulting favorability is very low.

Factors of Favorability

The factors of favorability used here describe broad, regional scale features that define an area as favorable in contrast to detailed features requiring samples and laboratory analysis. Each factor is described below sufficiently to guide the assessor in assigning a value to the factor for the entire or part of area being appraised. Much more detail could be included, but it would lead to complexity that would defeat the purpose of simplicity.

Precursor conditions (P)

Favorable precursor conditions consist of two general elements 1) the existence of a uranium province, and 2) a simple structural style before and leading up to the sedimentation process for the potential host sandstone. The presence of a uranium province is indicated by 1) abnormally abundant uranium in basement rocks, 2) an indication of uranium loss in basement rocks (Silver, 1976), or 3) the presence of one or more uranium deposits (particularly of another type and in nonsedimentary rocks) in the nearby region. Data on these factors may not be available in a frontier area so that use of the indication of a uranium province in determining the value of P could be downplayed. The more important element for sandstone uranium is the nature of tectonic setting before the beginning of host rock sedimentation--a condition that generally extended into the sedimentation period. The most favorable tectonic setting was one of a stable platform or foreland within the continental crust. Nearly equally favorable settings were the margin (coastal plain) of the continental shelf and intermontane basins of a mobile belt within pre-foreland areas. Geosynclinal and oceanic crustal settings are unfavorable.

Host rock formation (H)

The sedimentation of the host sandstone formation has three equally important elements to consider, namely, the time of sedimentation (T), the environment of sedimentation (E), and the resulting composition of the host unit (C). Thus:

$$H = T + E + C, \text{ where } H \text{ equals } 0 \text{ to } 1.$$

Time. - Based on the strong correlation of typical sandstone uranium deposits with carbonaceous plant fossils and their evolution, the age of the potential host formation must be Silurian or younger. Our present knowledge of the distribution of ores in sandstone formations of various ages allows us to choose the more important ages (a graph plot of geologic time vs tons of contained uranium will be compiled to guide evaluation). Formations of Carboniferous, Permian, Triassic, Jurassic, Cretaceous, Eocene, and Miocene ages deserve a full value of one-third for T; rocks of other than Silurian and younger ages are less likely to contain important deposits, and a value of one-tenth is suggested for T. The hosts for primary roll-type deposits are rocks of Tertiary age (and perhaps some late Cretaceous), whereas tabular deposits are in older formations.

Environment of Deposition. - The favorable environment of sedimentation of potential host sandstone formations is continental; marine environments are unfavorable, except for shore-line fluvial-related environments, which are favorable. Distinct continental basins on the order of 40 to 250 kilometers

or more across seem to be most favorable. Specific favorable environments include fluvial (braided, mixed load to bed-load channel fills, low-gradient water-saturated alluvial fan), lacustrine, deltaic, and strand-plain-(produces barrier island bar sands). Fluvial fans are especially favorable, and the mid-fan facies is most favorable. The edges of basins, within one-quarter of the diameter of the basin from the original or eroded leading edge (highlands side) of basins, are more favorable than interior areas (reflects mid-fan position). The presence of a well-developed unconformity at the base of the potential host sandstone is an additional sign of favorability. Deep marine and non-shoreline shallow marine facies are totally unfavorable.

Composition. - Favorable host units consist of relatively clean quartzose sandstone interbedded with mudstone, a situation of permeable beds restricted by impermeable beds that directed ore-forming waters. The favorable sandstone is most commonly medium- to coarse-grained and either tuffaceous (devitrified volcanoclastics) or feldspathic. It most generally contains either carbonized plant matter (silicified is unfavorable) or pyrite (iron-oxides in outcrop), or both. These latter materials provided the reducing environment. Pyrite may be derived from H_2S rising from underlying oil-gas fields through faults. Unfavorable sandstones are either quartz only (eolian) or dirty quartz-poor, generally termed graywacke.

Host Rock Preparation (A)

Preparation of the sandstone for uranium mineralization seems most likely to have taken place during diagenesis and resulted in alteration of rock minerals and the formation of new minerals. These changes are apparent in the color of the rocks. Favorable sandstones are generally light gray to white but may be shades of pink, yellow, and brown; mudstones are green and gray. Unfavorable colors are generally dark shades of red. Tabular deposits in Jurassic and older sandstone formations are most commonly in reduced (gray) rock where as roll-type deposits in Tertiary formations are at the interface of oxidized (pinkish) and reduced (gray) sandstone. The oxidized sandstone is updip and could be an outcrop feature indicating favorability for roll-type deposits.

Source of Uranium (S)

Favorability for large uranium deposits requires evidence for the existence of an adequate source of uranium at the postulated time of mineralization, generally shortly after sedimentation of the host unit. Furthermore, the position of the possible source must have been superjacent, either directly above or lateral to the potential host to have allowed transport of the uranium to the site of mineralization. If the potential source was below the potential host beds, it would be an unfavorable position. Two main sources have been cited for typical sandstone ores, either a granite or a tuffaceous sediment. Proposed granite sources were nearby granite-core mountain ranges where leaching of uranium (evidence needed) into surface and ground waters permitted uranium supply for mineralization. Thick tuffaceous mudstone member overlying the potential host sandstone member is a favorable source as would be a later tuffaceous formation that truncates the eroded edge of the potential sandstone host. An adequate source is the existence of one of the two sources; a more than adequate source would be the existence of both sources. The lack of a identifiable source for uranium is

probably the one factor that rules out many otherwise favorable sandstone formations.

Status of the Model

The above model statement and suggested method of its use are new to metal resource assessment; this approach was suggested by the oil-gas play analysis method of appraising undiscovered petroleum resources (Canada Dept. Energy, Mines and Resources, 1977; White, 1979; Mast and others, 1980). This initial attempt at developing a new methodology for metallic resource assessment is obviously incomplete; a second draft of the existence model will certainly show improvement. Further research is needed to extend the model perhaps along the lines of play-specific, prospect-specific (detailed guides for small scale exploration), and reserve-specific (comparable to of reservoir specific attributes) analyses. It is my proposal to do this research in the Uranium Resource Assessment Group over the next few years to develop and test a more complete existence model and play-like analysis not only for sandstone uranium deposits but other types of uranium deposits. This modelling and resource assessment methodology could also be applied to other types of metallic mineral deposits.

Probability of Existence

Once the degree of geologic favorability of region to contain large sandstone uranium deposits is established one needs to predict the probability of the existence of one or more ore deposits. Probability can utilize other parts of a genetic model, such as evidence for transport of uranium, the actual mineralization process, post-ore modification, and preservation. One could argue that parts of these stages should be in the above existence model, and perhaps evidence of uranium transport should be added as a fifth factor in the formula. The use of direct and indirect evidences of the presence of uranium for probability estimates is discussed by Finch and others (1980, p. 48-50). Development of a method to use these indicators plus other data to make an estimate of the range in probabilities of the existence and chances for discovery is being studied now and will continue. It is premature to make a statement at this time.

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EMPIRICAL RECOGNITION CRITERIA FOR UNCONFORMITY-TYPE URANIUM DEPOSITS APPLIED TO SOME PROTEROZOIC TERRANES IN THE UNITED STATES

By
J. Thomas Nash

Introduction

Ore is where you find it, so they say, and often the find is pure luck. Some unconformity-type deposits were found in uranium exploration programs with other environments in mind (Rabbit Lake, Cluff Lake, Key Lake, Koongara). Ranger was found on a concession acquired for base-metal exploration. Serendipity works, but how do we in the United States improve our odds now that we can review a decade of experience and dozens of discoveries in Australia and Canada? Models of many types are being developed today--what approach is best for these complex deposits? My conclusion is that in 1982 there is insufficient definitive information on ore formation processes to formulate reliable genetic models. Until additional deposits and districts are mapped, and diagnostic laboratory studies completed, I favor use of generalized empirical geologic criteria so that possibly favorable terrane will not be prematurely eliminated.

Strategies for mineral evaluation are highly varied, and terms are vague due to broad usage (e.g. Ruzicka, 1977, Wright, 1979, Finch, and others, 1980). Some comments on terms, as I use them, are required because the limitations and merits of any system cannot be appreciated unless the underlying philosophy and inuendos are known. Numerous discussions with knowledgeable friends over the past few years indicates that terms such as "empirical", "geologic", and "genetic" have subtle difference of meaning.

Evaluation schemes are based on at least four approaches (fig. 1). The starting point for most approaches is field observations, which initially are relatively free of interpretation. An opposite approach is through concepts, often based on little information. Between these to end-members are methods that emphasize observed and interpreted physical geology (ore habitat) or physico-chemical conditions of ore formation. It is important, I think, to recognize that habitat can be observed, although the relationship of ore to features commonly is moot, whereas ore processes cannot be directly seen in the field, but their record in isotopes and fluid inclusions can be direct evidence of conditions of ore formation. To me, the term "geologic" should be applied to the habitat side of the box (fig. 1), and "genetic" used for the process side. Ideally, and ultimately, thinking and modelling encompasses all four approaches. I add the modifier "empirical" to geologic to note emphasis on observations rather than interpretations. The advantage of the empirical geologic method is that it is relatively objective and generalized but it has the disadvantage of being nonspecific--thus nonessential features probably are included. Finally, I am presenting a list of criteria, not a model, because no systematic relationship of cause and effect has been established. Comments are offered on possible roles for individual criteria to explain the choice, but this is not presented as a geologic or genetic system.

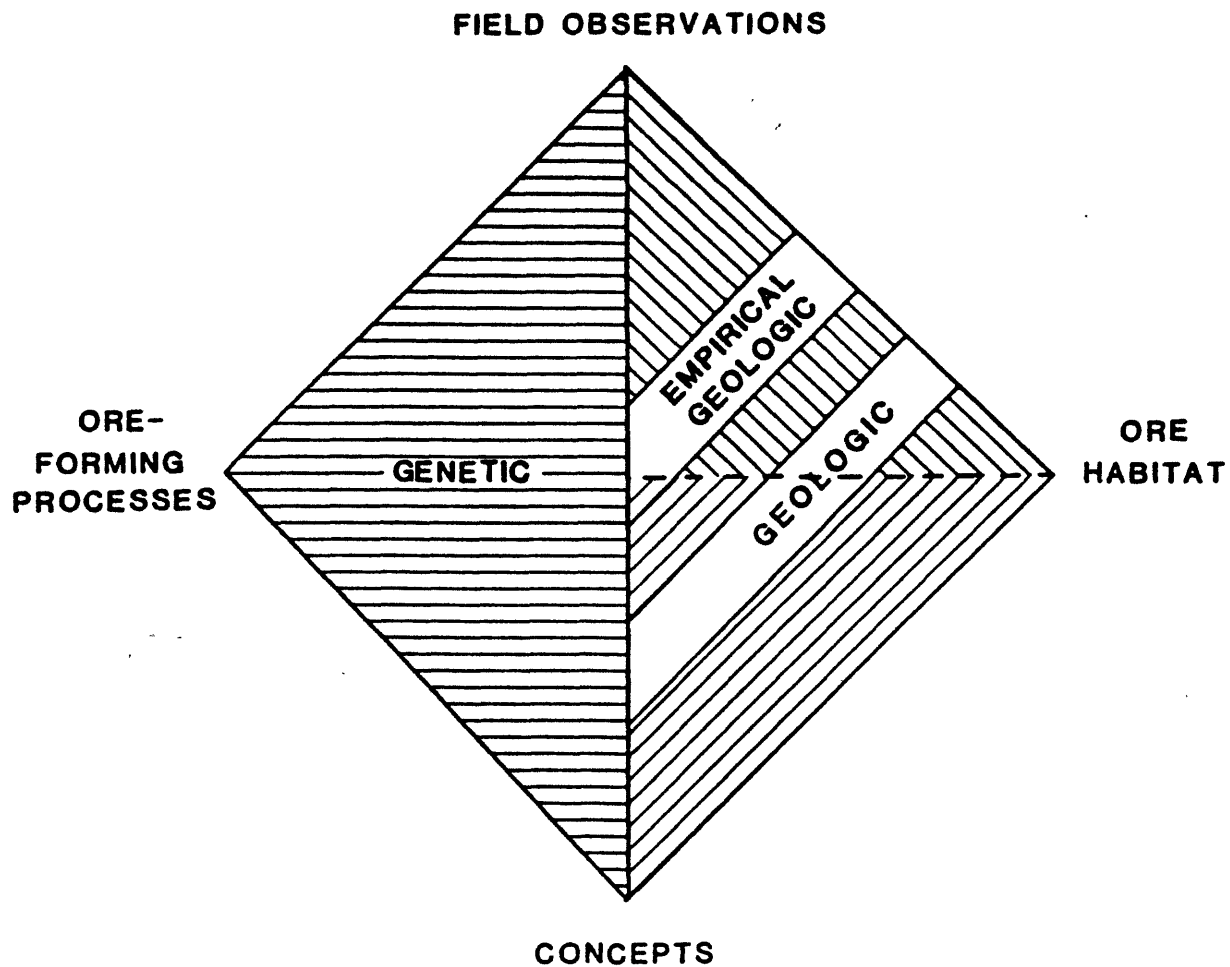


Figure 1.--Schematic diagram of relations between four approaches to resource evaluation. Geologic models emphasize physical, geologic features that can be seen in the field, whereas genetic models emphasize physicochemical conditions that cannot be seen.

Scale is an important consideration in evaluation strategy. The first step toward identifying unconformity-type deposits in the U.S. is location of favorable regions in the size range about 1,000 to 10,000 km². This is approximately the scale of NURE quadrangle investigations which effectively used 1:250,000 base maps. The criteria I propose are for a first round evaluation and use, as much as possible, features shown on geologic maps of this scale plus regional geochemical or geophysical surveys. Follow-up investigations and drilling programs need more specific criteria and more detailed data sets.

The geologic habitat of unconformity-type deposits is shown schematically on figure 2. Basement rocks are Archean granitic rocks (no. 1, fig. 2). Unconformably overlying the basement is several thousand feet of Proterozoic sedimentary rocks (no. 3, fig. 2), that are infolded and metamorphosed with the basement (no. 4). The metamorphic rocks are retrograded to greenschist grade along fault zones (no. 5), some of which contain ore. Following erosion, the metamorphic rocks were covered by sandstones (no. 7), which later were faulted and intruded by mafic dikes (no. 8). Known uranium deposits are near the subsandstone unconformity in metamorphic rocks or sandstone. More detailed information is contained in papers by Dahlkamp (1978), Hegge and Rowntree (1978), and Hoeve and Sibbald (1978). Reviews by Kalliokoski and others (1978), Eupene (1980), Nash (1981), Dahlkamp and Adams (1981), and Nash and others (1981), offer additional information and speculation.

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Empirical Recognition Criteria

Eight features observed in the deposits discovered to date in the Northern Territory and in Saskatchewan are proposed as recognition criteria (table 1). They are arranged in order of decreasing age but are not ranked to avoid bias. Insofar as possible, the criteria are only descriptive, and none have been proven to have been factors in the formation of an ore body. Also, I believe that an ore body can form with one or more of the criteria lacking, but with the probable consequence of lower grade or tonnage than prototype examples.

Table 1.--Empirical Recognition Criteria for Unconformity-type deposits
[Criteria are arranged in order of decreasing age]

8. Post-cover rock deformation
7. Covering sandstone
6. Paleosurface
5. Retrograde metamorphism
4. High-grade metamorphism
3. Supracrustal metasediments
2. Pre-metamorphic unconformity
1. Granitic basement

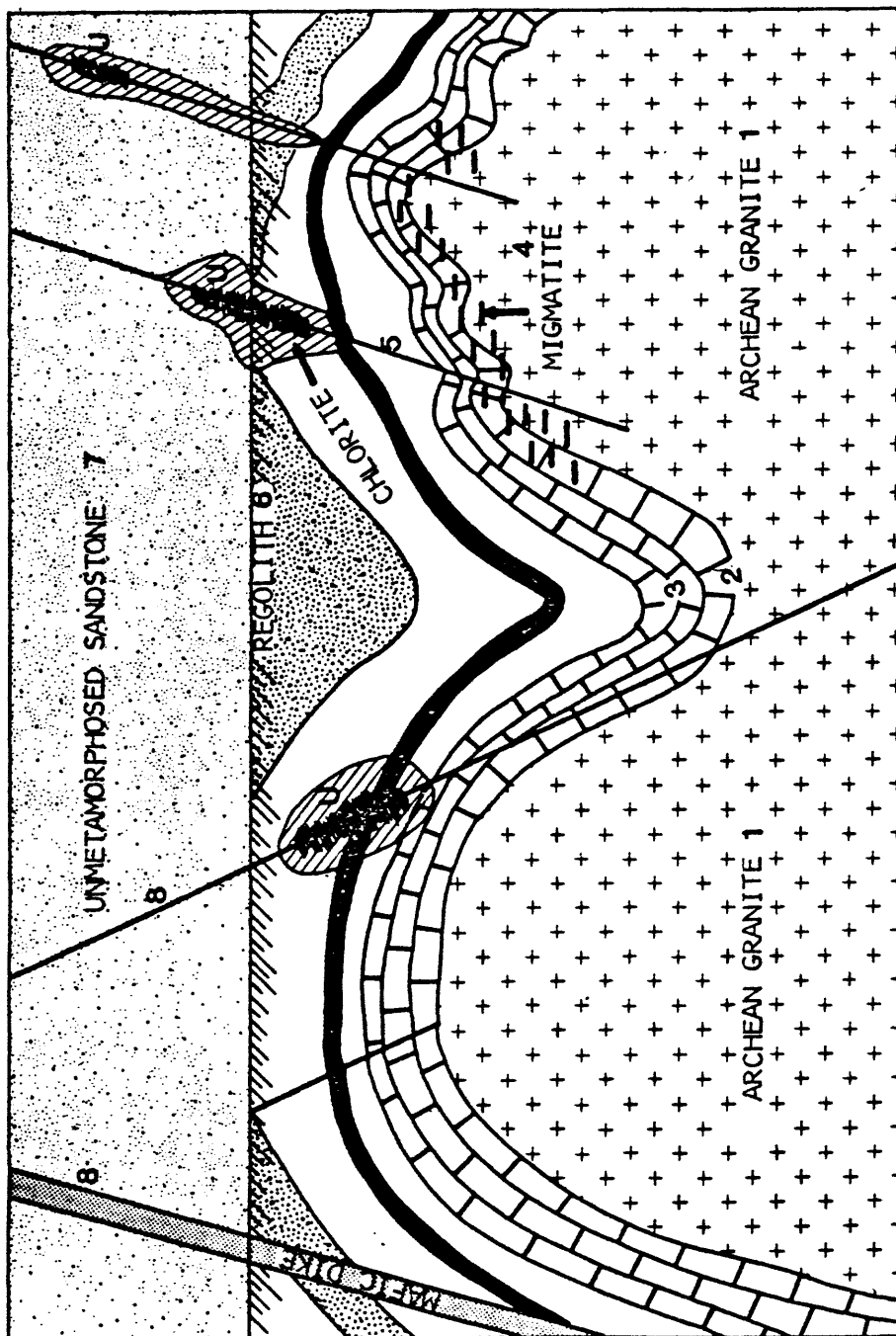


Figure 2.—Schematic cross section showing geologic habitat of unconformity-type uranium deposits. Numbers correspond to criteria in Table 1 and discussed in text. No scale.

1. Granitic basement.--Granitic rocks, commonly in the form of reactivated gneiss domes, occur near the known deposits and probably were the source of clastics for the host rocks and also probably were the ultimate source of uranium. Some of these rocks have demonstrated anomalous uranium content. Basement rocks in Northern Territory and in Saskatchewan are Archean, but I see no geochemical reasons why younger granites or rhyolites could not serve a similar role.
2. Pre-metamorphic unconformity.--There are two unconformities in the rock sequences that contain the known deposits but the unconformity on granitic basement tends to be ignored. This unconformity establishes age relationships and allows possible uranium enrichment during erosion and sedimentation.
3. Supracrustal metasediments.--The rocks that host or underlie the known deposits are in a most general sense supracrustal Proterozoic rocks as defined by King (1976, p. 72): "sedimentary and volcanic rocks that were laid down on the surface of the earth, on a basement of rocks that had a more complex metamorphic and plutonic history." Many of these rocks in the type areas have been interpreted to be marginal-marine sequences (Nash, 1980). There is permissive evidence for uranium preconcentration during the diagenesis of the marginal-marine sequences. Carbonate rocks, commonly magnesian and with algal structures, interbedded with carbonaceous pelites and evaporites or sebkha facies, are a key to recognizing these rocks in the field or literature. Sedimentation was probably in intracratonic rifts characterized by gradual extension.

An additional attribute that many specify is an early Proterozoic age for the supracrustal rocks because this is the age in the known districts. There are plausible reasons for this relationship, such as the unique newly oxygenated ground water about 2.2 to 1.8 b.y. ago. However, there are several examples of black shales of much younger age that contain significant amounts of uranium. I know of no geochemical reasons for a change in the behavior of uranium over the Period about 2.2 to 0.4 b.y. Thus, I conclude that restricting the search to supracrustal rocks of early Proterozoic age could eliminate some potentially favorable younger terrane.

4. High-grade metamorphism.--Amphibolite or granulite grade metamorphism is characteristic of the known districts. During the metamorphic event the basement granitoids rose and the covering supracrustal rocks were partially melted onto the granitic cores. The behavior of uranium during the metamorphism is essentially unknown. Uranium may have been mobilized in the vicinity of the gneiss domes and migrated outward into sites of redeposition, or possibly remained essentially in situ but was separated from carbonaceous material to form reactive uranium phases and make the schists "fertile", analagous to "fertile granites." However, some unconformity-type deposits do occur in lower grade metamorphic terrane, as at Rum Jungle, and these deposits tend to have lower tonnage.
5. Retrograde metamorphism.--The known deposits typically are in zones of penetrative deformation and retrograde metamorphism. Magnesium metasomatism is characteristically developed in and around deposits, as shown by chlorite, magnesite, and other magnesium minerals. The deformation tends

to follow graphitic beds. Electromagnetic methods, especially airborne EM, can detect the sheared and altered zones to a depth of about 200 m if covering rocks are not highly conductive.

6. Paleosurface.--The empirical association of deposits with unconformities, and hence the unfortunate name for the class of deposits, now is highly debated. The preliminary evidence of the early 1970's suggested to many geologists that the deposits formed by supergene processes operating below the paleosurface. Then came the new facts that some deposits such as Key Lake and Midwest Lake occurred both below and above the unconformity and others such as Collins Bay occurred entirely above the unconformity. Also, it was appreciated by some that other deposits such as Koongara No. 2, Jabiluka Two, and Eagle Point, show little or no relation to the overlying unconformity. Some deposits such as Michelin and Oklo which have features in common with unconformity-type deposits are in sequences lacking unconformities. My conclusion is that these deposits can form without processes operating at the paleosurface. In concept, supergene enrichment can upgrade the ores and chiefly for this reason the paleosurface criterion is included. The zone immediately below the unconformity should not be given as much attention as most advocate; a zone about 500-m thick above and below the unconformity should be examined, and fault zones in the supracrustal sequence with no spatial association with the unconformity also should be considered.
7. Covering sandstone.--The known deposits display a clear spatial relation to overlying or hosting unmetamorphosed sandstones. Some (e.g. Kallioikoski, and others, 1978) specify that the sandstone must be nonmarine, which is probably useful. I prefer to think of the cover rock as an aquifer, so its genesis is not as important as its physical character. This leads me to consider other types of aquifers that are capable of introducing oxidizing ground water that can upgrade uranium derived from the supracrustal sequence. The role as aquifer is a plausible explanation for the association of known deposits with large sandstone bodies in broad basins covering more than 50,000 km².
8. Post-cover rock deformation.--In the known districts the covering sandstones have undergone little deformation but are locally cut by high- and low-angle faults. These faults carry ore in several deposits and in general are probably reactivated faults. These young faults appear to focus remobilization of uranium and permit uranium transport into the sandstone from underlying supracrustal rocks. Mafic dikes occur in or near many of the deposits and in the Athabasca area have the same age as a stage of uranium minerals. The dikes seem important as heat sources for hydrothermal systems that remobilize and upgrade uranium concentrations. The mafic dikes are characterized by strong magnetic anomalies in airborne surveys.

Presence of uranium anomalies and occurrences might be another criterion because uranium is a good guide to uranium deposits. On the other hand, near surface uranium occurrences are normally highly oxidized, difficult to characterize, and generally are not a reliable guide to a specific type of uranium deposit. Further, abundance of uranium occurrences has no demonstrated relationship to ore potential. Thus, I conclude that uranium occurrences can be both useful and misleading, and

probably are not a necessary criterion for the presence of a specific type of deposit.

Application of Criteria to Some Proterozoic Terrane

The United States clearly does not have large areas underlain by Proterozoic metamorphic rocks (within 1.5 km of the surface) (fig. 3), but several areas have been recommended as possibly favorable for the occurrence of unconformity-type deposits. Eight areas will be considered in the Lake Superior Region, Northern Rocky Mountains, Southern Basin and Range Province, and Central Appalachian Region as a general illustration of how the criteria can be applied. As noted earlier, the criteria are not proven, and my knowledge of the areas under test is limited, hence the comments on favorability made here are certainly not final. Also, other types of uranium deposits not considered here may well exist.

1. Michigamme Formation/Jacobsville Sandstone--In the Iron River 1° X 2° quadrangle, Michigan and Wisconsin, (Cannon, 1978; Frishman, 1981) basement rocks are Archean granite, granitic gneiss, and a variety of mafic metamorphic rocks. The unconformably overlying early Proterozoic Marquette Supergroup, which includes the Michigamme Formation, was folded and metamorphosed (greenschist grade in the area of interest) 1.9 to 1.7 b.y. ago. Details of early Proterozoic sedimentation are lacking but the known Michigamme lithologies are chiefly mafic volcanic rocks, metagraywacke, and slate. Iron formations in the Michigamme are the volcanic (Algoma) type, not the shallow water Superior type. No carbonates are reported from the Michigamme. In the Iron River quadrangle the Michigamme appears to have been deposited in the deep-water turbidite environment of the northeast-trending Animikie basin (Cannon and Klasner, 1975; Larue and Sloss, 1980). Thick mafic flows rest unconformably on the Michigamme along most of the sub-Jacobsville unconformity. The Jacobsville Sandstone, probably about 1.0 b.y. old, overlies the flows. Sedimentary structures and lithology of the Jacobsville closely resemble the Kombolgie and Athabasca Formations (Kalliokoski, and others, 1978). Post-Jacobsville faults are rare and no younger intrusive rocks are reported. The Jacobsville Sandstone is a good aquifer, and several uranium occurrences are known near it, but other features of the Michigamme/Jacobsville package do not fit the postulated criteria. Particular problems are the deep-water sediments in the Michigamme and the thick flows between the supracrustal rocks and the sandstone.
2. Thomson Formation/Fond du Lac Sandstone--In east-central Minnesota basement is the McGrath Gneiss, a pluton of probable early Proterozoic age which is one of the most radioactive rock units in Minnesota (Ojakangas, 1976). The Thomson Formation, older than about 1.7 b.y., unconformably overlies the McGrath. Most of the Thomson is metagraywacke, metasilstone, and slate of turbidite origin (Morey and metagraywacke, metasilstone, and slate of turbidite origin (Morey and Ojakangas, 1970). However, at one locality southeast of Denham more than 75 m of marble and quartzite are present and contain clasts derived from the McGrath Gneiss (Keighin, and others, 1972). The Thomson was tightly folded and metamorphosed to greenschist facies 1.7 b.y. ago. The Fond du Lac Sandstone of late Proterozoic age unconformably overlies the Thomson but nowhere is the unconformity exposed. The Fond du Lac is a permeable

quartzose sandstone of fluvial-deltaic origin (Ojakangas, 1976) and is very similar to the Athabasca Formation (R. W. Ojakangas, written commun., 1980). A few faults cut the Fond du Lac, but all reported intrusive rocks are older than it. This package of rocks seems to meet only a few of the recognition criteria proposed here. If more shelf sediments can be identified on the flank of the McGrath Gneiss that would be a more favorable zone than the typical deep-water metasediments of the Thomson.

3. Sioux Quartzite area.--The middle Proterozoic Sioux Quartzite of southwestern Minnesota and eastern South Dakota has attracted interest because its age, extent, and lithology resemble the Athabasca Formation (Ojakangas, 1976). Basement rocks, known from sparse outcrops and scattered wells, are mostly granite and mafic schist of probable Archean to early Proterozoic age (Lidiak, 1971). No supracrustal rocks, as defined earlier, are present. The sub-Sioux unconformity is nowhere exposed, but deep-tropical weathering has been advocated to explain the aluminous clays in the Sioux. The Sioux is generally a very clean, well-sorted, thoroughly indurated quartzite, although some conglomerate and clay-rich beds occur locally. The Sioux was gently folded and intruded by some mafic dikes. The Proterozoic package in this area fits the recognition criteria very poorly. In particular, the pre-Sioux rocks do not resemble those in the productive districts, and the Sioux probably was too well cemented to be an aquifer in the Proterozoic (it is not one today).
4. The Belt Supergroup.--The middle Proterozoic Belt basin (Harrison, 1972) of the northwestern United States and the sedimentary rocks in it are in many ways the most similar to the productive areas that I know of. Several other aspects of the history of these rocks do not compare well with the productive areas, but some variants might be possible. Basement in several places is known to be pre-Belt granitic rocks about 1.5 b.y. old and more are being identified as mapping and dating progress. The Belt basin has extent and facies reminiscent of the Pine Creek Geosyncline, especially the abundant shallow-water sediments including carbonates. Metamorphism of the Belt rocks in the Proterozoic was very low grade, but high grades were reached adjacent to some Cretaceous-Tertiary intrusions as in the Idaho Batholith. There are several unconformities in the section, and several covering sandstones such as the Cambrian Flathead Sandstone and Addy Quartzite in the eastern and western parts of the Belt Basin. Perhaps we should look closely for uranium in a unit such as the Wallace Formation and signs of remobilization in zones of contact metamorphism--a possible variation on processes in the prototype unconformity deposits.
5. Uintah Mountain Group.--Proterozoic rocks in northeastern Utah are believed to have formed in a pericontinental basin similar to the Belt basin, but the typical shallow-water sediments of the Belt Supergroup are lacking (Crittendon and Wallace, 1973). Oldest rocks in the area are Archean metamorphic rocks including the Red Creek Quartzite (King, 1976). The Uintah Mountain Group, of probable early Proterozoic age, is predominantly fluvial arkose and quartzite with siltstone and shale of paralic-sublittoral deposition. No carbonate rocks are known. The 950 m.y. old Red Pine Shale overlies the Uintah Mountain Group. This package of rocks has very little in common with the productive districts.

6. Apache Group/Troy Sandstone.--Middle to late Proterozoic rocks in central Arizona may have favorability for uranium deposits with unconformity-type features if age and metamorphism characteristics of the Saskatchewan and Northern Territory deposits are not applied literally (which I favor). Basement rocks are 1.4 b.y. and older granites, metarhyolites, and schists (King, 1976). The Apache Group (Shride, 1967) fits the supracrustal criterion very well as it contains abundant shallow-water (or lacustrine) sandstones and algal carbonates. Metamorphism is very low grade. The Dripping Spring Quartzite of the Apache Group contains numerous deposits and occurrences (Granger and Raup, 1969) and the uranium in the upper part of the Dripping Spring has recently been interpreted as initially enriched during diagenesis (Nutt, 1981). The Apache Group was weathered but not deformed or metamorphosed prior to deposition of the middle Proterozoic Troy Quartzite. The Apache Group and Troy Quartzite were faulted and intruded by thick mafic dikes and sills at about 1.2 b.y. The metamorphic/hydrothermal event produced by the mafic intrusions probably caused remobilization of uranium into some ore deposits. I agree with Nutt (1981), that events and processes in the Dripping Spring Quartzite were probably very similar to those in the prototype unconformity deposits. Major uncertainties are the effects of low-metamorphic grade as compared to higher grades in the major deposit areas, and the role the Troy Quartzite might have had, if any.
7. Van Horn area, West Texas.--This area has been investigated during the NURE program with uncertain results (Davidson and others, 1980). Application of the proposed recognition criteria to this area points to the sub-Hazel unconformity as a more likely locus for deposits than the younger sub-Van Horn unconformity. Although basement rocks and metamorphism in the area do not resemble the type areas, the late Proterozoic Allamore Formation contains talcose phyllite and dolomite that are a fair fit of the supracrustal rock criterion. The late Proterozoic Hazel Formation, consisting of conglomerate, sandstone, and limestone, rests unconformably on the Allamore. Davidson and others, (1980) report uranium anomalies near the sub-Hazel unconformity but did not comment on the possible similarities to unconformity-type deposits as they seemed to be focusing on the younger sub-Van Horn unconformity. The Allamore/Hazel package may warrant further work. This example illustrates how empirical recognition criteria can be used to interpret geochemical anomalies.
8. Grandfather Mountain window.--This area in western North Carolina contains more than 20 uranium occurrences that have aroused unusual interest for an eastern United States area, and there has been speculation that the occurrences may be in an unconformity-type environment. The occurrences are in basement rock, the ca. 1.0 b.y. old Wilson Creek Gneiss, a pluton that has been extensively deformed (Bryant and Reed, 1970). Narrow fractures and cataclastic zones in the gneiss contain pitchblende and hexavalent uranium minerals with minor associated alteration. No supracrustal metasediments (in the sense used here) are known in the area. The basement rocks are overlain unconformably by poorly sorted conglomerate, arkose, and siltstone of the late Proterozoic Grandfather Mountain Formation, a poor aquifer. To me, the rocks in this area do not fit the recognition criteria very well. The uranium veins, and associated graphite and phyllonite are enigmatic (R. I. Grauch, oral commun., 1976) and of interest as indicators of possible additional uranium resources, but not of the unconformity type.

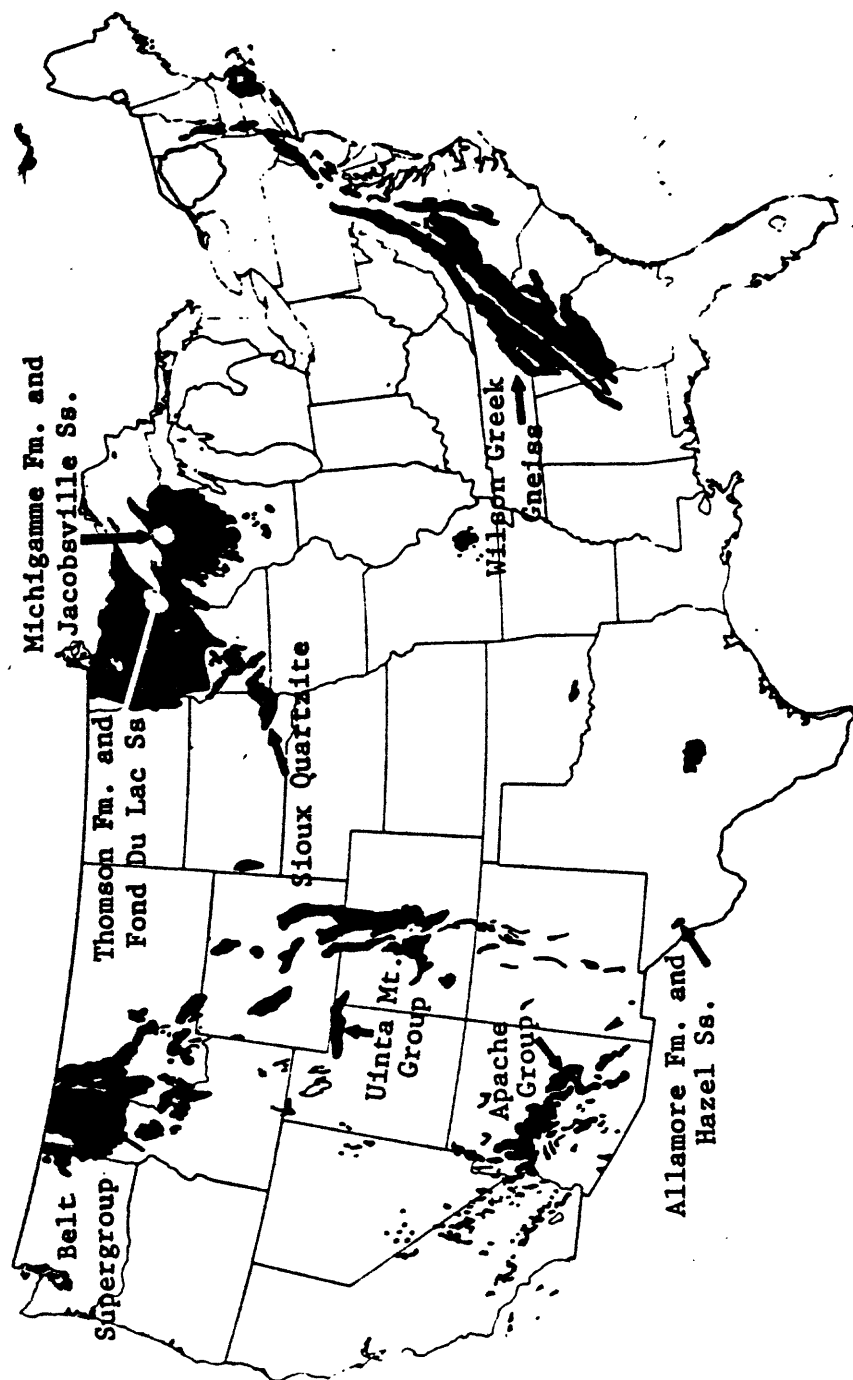


Figure 3.—Map of the conterminous United States showing distribution of exposed Precambrian rocks (from King, 1976), and the location of eight geologic sequences discussed in the text.

Concluding Remarks

The empirical recognition criteria proposed here obviously need refinement and testing through additional research. The criteria seem to be useful for a general comparison of new areas with productive districts, but I fear that literal application of empirical criteria can be misleading. Some of the criteria may be insignificant or sufficient, but those necessary for ore formation need confirmation. If the genesis of unconformity-type deposits involves many stages, and I believe it does, then what is the effect of missing a stage? Some missing stages probably would merely decrease grade or tonnage, but others might negate possibilities for ore formation altogether.

More specific criteria and integrated geologic models are needed, but until we truly understand these complex deposits we must be wary of dogmatic views based on preconceptions (F. J. Dahlkamp, oral commun., 1981). Better understanding should allow recognition of new variations on known deposits and suggest new favorable terrane. One speculative variation that looks promising to me is ore formation during or after contact metamorphism in rocks that meet criteria 1 to 3, as in the Apache Group (Nutt, 1981) or Belt Supergroup. If we use foresight, rather than hindsight, some of the areas considered here that do not seem to be favorable for known unconformity-type deposits, may well be favorable for other varieties.

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BADLANDS-TYPE MOLYBDENUM-URANIUM DEPOSITS IN SANDSTONE

By

William H. Raymond

Regional Setting

Molybdenum and uranium occur in lenticular zones in basal Oligocene sandstone beds of the Chadron Formation in paleovalleys that were carved into the upper surface of the Upper Cretaceous Pierre Shale. The Pierre underlies or crops out over much of western South Dakota; it is overlain by remnants of the Chadron Formation mainly in the Big Badlands in the southwestern part of the state east and southeast of the Black Hills. A similar geologic situation occurs in the subsurface portions of western Nebraska where sandstone of the Chadron Formation is present in paleovalleys in both the Pierre and Niobrara Formations. Permeable clastic sediments filling paleovalleys cut into impermeable carbonaceous shale and a source of metals available to the groundwater system constitute the framework for deposition of this type of deposit. Although the Chadron-Pierre relationship is the one in which currently-known deposits occur, it is reasonable to expect that similar rocks of other formations in other areas would function equally well to produce mineral deposits of this type.

Deposit Characteristics

Molybdenum and uranium occur as water-soluble oxides in lens-shaped zones at or near the base of the Chadron Formation. The major molybdenum mineral is an amorphous yellow oxide which is visually indistinguishable from jarosite (or carnotite) with which it occurs. Nodules as large as 4 in. in diameter are common in some places; the cores of the nodules are sometimes black or dark blue changing outward to yellow or brown. Black core material may be jordisite (amorphous MoS_2); and blue cores are usually ilsemannite (amorphous $\text{Mo}_3\text{O}_8 \cdot n\text{H}_2\text{O}$?).

Drill hole data have shown that the Mo occurs in the subsurface as jordisite (with associated marcasite) that is oxidized to the yellow oxide (resembling ferrimolybdite, carnotite, or jarosite) near the weathered surface.

The yellow molybdenum oxide may be a molybdenum oxy-sulfate or a multiple oxide of Mo. Ilsemannite can be converted to a similar-appearing yellow oxide by bubbling oxygen through it in solution.

Other minerals associated with the deposits include barite, selenite, calcite, silica, and various unidentified minerals of selenium, arsenic, vanadium, strontium, and rare earth elements. Many of these elements have been transported in the groundwater and are present in very high concentrations in bits of fossil bone. Some are known to be present in detrital mineral grains in the Chadron Formation.

Uranium occurs as several oxide and phosphate minerals including carnotite, uranocircite, and others (Moore and Levish, 1955). The distribution of uranium minerals is much more restricted than that of molybdenum minerals.

Mine/Outcrop Characteristics

Mo and U oxides occur in lenses of varying thickness in clastic-material ranging from pebble conglomerate to very fine grained sandstone. High-grade areas are usually stained bright yellow with seams of bright yellowish-green where U oxides are present. In detail, these minerals are an earthy interstitial filling which occupies space between sand grains.

Radioactivity is reported to show an inverse equilibrium, that is, eU readings indicate less U than chemical analyses.

The discovery site at Indian Creek, southwest of Scenic, South Dakota, contains an approximately 10-ft.-thick body of Mo-U-bearing sandstone and conglomerate the base of which is about 20 ft. above the top of the Pierre Shale and about 100 ft. from the north wall of a paleovalley (Red River Valley of Clark, 1937). The paleovalley is about 8 mi. wide at the Indian Creek locality.

Further into the valley (about 1 1/2 mi. from the north wall) is a lens of Mo-bearing fine grained sandstone which is over 20 ft. thick. Other lenses up to 30 ft. thick have been discovered in the channel 1/4-2 mi. from the north wall. These thicker, lower-grade, predominantly Mo-bearing lenses are mainly red orange, the color not clearly related to mineralization. Yellow Mo oxides occur near the bases of the lenses; perhaps 2 ft. of yellow oxide (including abundant jarosite) and 20 ft. or more of overlying red-orange, banded material which is not readily distinguishable from normal unmineralized sandstone common in that part of the badlands.

Genesis

The localization of the Mo-U minerals was controlled by groundwater flowing through permeable sandstone and conglomerate which were deposited in a stream channel cut into the underlying impermeable carbonaceous Pierre Shale. Mo-U-bearing groundwater produced deposits where the oxidized solution was reduced by carbonaceous material from the shale. Therefore, in the Chadron section in the Red River Valley (which reaches a maximum thickness of 175 ft.) the mineralization is generally restricted to the lower 35-40 ft.

The question of the origin of the metals is still open: a long-standing theory is that the metals were leached from overlying volcanic ash by descending meteoric water; other evidence suggests the possibility that Mo and U may have entered the groundwater system from deposits in the Black Hills which are updip from the badlands area; a third possibility is that metal ions were supplied from below through myriads of fractures from an underlying geothermal water system. The latter source seems most probable because a dwindling geothermal system has been delineated, a fracture system has been recognized, barite and selenite are reasonable products of the process, and anomalous Mo has been found in some of the fractures.

It is reasonable to expect that similar geologic frameworks may exist in other areas and may involve other formations.

Prospecting Techniques

The geologic framework is easily recognizable--that is: permeable clastic sediments in a channel in impermeable rock, and a source of carbonaceous material available to the system to reduce oxidized groundwater.

Check all yellow, black, and red amorphous matrix material in otherwise porous clastic rocks for Mo. Check outcrops and samples of such rocks for radioactivity. Watch for sulfate minerals such as barite and gypsum as related to fracture systems in clastic rocks. The topographic expression of such fracture systems are sometimes more visible on topo maps than on the ground.

Airborne radiometric surveys may be useful in delineating buried or exposed deposits; and gravity methods may be useful in exploration for buried channels.

Large paleovalleys such as the Red River Valley southwest and south of Scenic, South Dakota, are normally expectable at relatively wide intervals. Hence, one should not expect to find another one nearby. In the case of southwestern South Dakota, a second paleovalley of the same sort has been discovered in drill holes in western Nebraska. It would be remarkable if another contemporaneous deposit were discovered between the two.

Paleovalleys in the Pierre and Niobrara Formations can be recognized easily by the absence of the highly-colored paleosol (the Interior beds, presumably of Eocene Age) wherever significant post-Cretaceous downcutting has occurred.

Water sampling may be very valuable as an exploration tool because of the water-soluble nature of the minerals.

Economics

To date, the richest lens of Mo-U ore in the Scenic area (at Indian Creek) has not been exploited.

Semi-quantitative spectrographic analyses from hundreds of samples range in value from 0 to greater than 10 percent Mo from 0 to about .3 percent U. The minerals in which these metals are contained are largely water soluble. In situ leaching has been considered; normal mining and chemical treatment have been considered also because placer gold and many detrital minerals are also contained in the deposits, some of which may be economically recoverable.

The deposits contain anomalous amounts of selenium and arsenic (in places) which may be an environmental detriment or a profitable by-product or both.

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OCCURRENCE MODEL FOR SEDIMENTARY MANGANESE DEPOSITS

By

William Cannon and Eric Force

All of the world's large manganese deposits are either primary sedimentary accumulations or supergene enrichments on manganese sediments. The more important class of sedimentary deposits are what we call marine transgressive deposits. These account for 80% of world manganese resources and include the Nikipol and Chiatura deposits of the Soviet Union, Groote Eylandt, Australia, Molango, Mexico, Moonda, Bagon and Morro do Urucum, Brazil. All of these deposits are related in that they occur in transgressive marine sequences commonly only a few tens of meters, but occasionally as much as 300 meters, above the unconformity at base of the marine sequence. The host rocks are commonly widespread shallow marine, dominantly clastic, sequences deposited on stable platforms, although in some cases the platforms have been reactivated by post-ore tectonism.

The manganese ore consists of beds of manganese oxides, carbonates or mixture of both. Known deposits show a great range of ages (lower Proterozoic to Oligocene), paleolatitudes (tropical to temperate), salinities (brackish to highly saline), climatic regimes (humid to arid). Local sedimentologic settings of ore deposits also vary widely. In short, no common denominator seems to link these deposits other than their unmistakable genetic dependence on marine transgression. As a result, no detailed occurrence model is possible at this time. We feel, however, that the awareness that shallow marine transgressive clastic sequences could bear important manganese ore deposits, a fact not generally appreciated in North America, is important for anyone working with these kinds of rocks. Be suspicious of any earthy looking beds, they may be weathered manganese oxides or carbonates. Also be suspicious of carbonate beds, especially dolomitic-looking (brownish weathering) beds or nodular carbonate beds. They could be manganese carbonates.

Important manganese ore beds and their subeconomic fringes are large, covering hundreds of thousands of square kilometers, so although detailed exploration guides cannot be devised, the targets are large and might well be found by reconnaissance field examination if we are on the lookout for them.

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LATERITE-TYPE BAUXITE--AL-GA

By
Sam H. Patterson

Setting

Laterite-type bauxite occurs mainly in tropical countries and particularly in regions of heavy rainfall. Most deposits are under only thin (1-5 ft) soils on peneplained uplands. The typical colors are shades of red and brown.

Deposits Characteristics

Gibbsite is the most common, and boehmite is the second most abundant bauxite mineral in laterite-type deposits. Mineral impurities are mainly goethite, hematite, quartz, kaolinite, and titanium minerals (principally clay-size anatase). The bauxite minerals occur in a wide variety of forms, including pisolites, nodules, earthy and clayey material, blocky and tubular structures, vein and vug fillings, blocky masses, and others. Some deposits are soft massive material or layers of uncemented pisolites, but others are lithified and blasting is required in mining. Thicknesses of deposits mined range from 7 or 8 feet to more than 60 feet.

Genesis

Laterite-type bauxite deposits form by chemical weathering that removes the more soluble components of the parent rock and adds OH groups and O to the ones remaining. Silica, alkalies, and alkaline earths are the major components leached and Al, Ti, and generally Fe are concentrated.

Bauxite at various places in the world has formed on virtually every rock type containing aluminum. Many large deposits have formed on basalt, and others on several types of metamorphic, igneous, and sedimentary rocks. The billions of tons of bauxite in the Weipa District, Australia formed on a clayey sandstone containing as little as 4 percent Al_2O_3 .

Economics

Individual deposits vary greatly in size. An isolated deposit or district containing as much as 10 million tons would attract little interest, unless in an unlikely discovery in an industrialized nation. Deposits commonly contain a 100 million tons and districts may have several hundred million tons or even as much as three billion.

Cost factors include mining, transportation, and Bayer processing to recover Al_2O_3 . Bauxite containing only gibbsite (trihydrate ore) is by far the cheapest to process and boehmitic (monohydrate ore) is the most costly, because higher temperatures, pressures, and caustic (soda ash) concentrations are required. Mixed bauxite (gibbsite + boehmite) is of intermediate cost to process.

Grades (in Al_2O_3 content) of bauxite mined range from 35 to 65 percent. Silica contents are critical, and rarely as much as 10 percent can be tolerated.

The form of SiO_2 is also critical--quartz, particularly of sand size or larger, does not react appreciably with the Bayer caustic. Whereas, clay-size quartz and kaolinite do react and form complex silicates and greatly-increase Bayer costs. Phosphate which occurs in minor quantities in some bauxite also causes problems. Organic matter (as much as 0.5 percent) also causes problems.

The principal environmental factors are rehabilitation of mined lands, disposal of Bayer plant waste (red mud), escaping caustic and gaseous emissions from aluminum smelters (F1 and maybe Hg).

About 80 percent of the world gallium production (15-20 tons per year) is a by-product of Bayer processing of bauxite. The geochemical behavior of Ga is similar to that of Al. Presumably Ga occurs in substitution for Al in bauxite minerals. The average Ga content of bauxite is about 50 ppm. Ga is likely to be in great demand (thousands of tons per year) in the future when man moves into space.

Prospecting Techniques

- Geologic -- Look for old upland plateaus and red and brown subsoils. Pisolites and light-colored small concretions, vug fills, tubular structures, and vein fillings can be helpful. However, some of the large deposits lacked eye-catching characteristics and were recognized only by soil analysis. Stunted vegetation may also be a guide.
- Get analysis! -- The weight lost with heat can be used in the field.
- Geophysical -- None reported really successful.
- Geochemical -- No help--Al or mineral contents of representative samples have to be determined.

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LITHIUM-RICH CLAYS
By
Sigrid Asher-Bolinder

Introduction

Today the United States produces three-quarters of the Free World's lithium, and uses half of that production itself. Depending on the types of batteries developed for powering electric vehicles, and the long-range development of nuclear fusion, the U.S. and world demand may greatly increase in the next two to four decades.

The two lithium producers in the U.S. now process domestic spodumene and an unusual playa brine for lithium. They believe their reserves sufficient to meet future demand (Evans, 1978, p. 384). To hedge their bets, however, they and other mining companies are exploring and negotiating production of high-lithium brines from the salars of the Altiplano of Chile and Bolivia to ensure their ability to meet future demand.

The U.S. Geological Survey's appraisal work of domestic brines and nontraditional clay sources has produced evidence of many anomalous occurrences of lithium (Vine, 1980, is a summary of that program's efforts). Yet to my knowledge, no model has been proposed to explain (the majority of) these occurrences. This is a first attempt to explain what the sources, enrichment mechanisms, and traps for lithium in nontraditional clays might be. This model draws heavily on the observations of others; hence, the bibliography is included.

What Factors Create Lithium-Enriched Clays?

I. Closed-basin deposition of ash-derived? smectites

Modern playas in closed basins of the Basin and Range Province, Tertiary paleobasin sediments exposed on flanks of bounding mountain ranges, the paleobasins of rift regions such as the Rio Grande Rift, and intra-caldera moat-fill sediments have the potential to provide traps for lithium-clay accumulation in the forms of altered ashes and lacustrine clays. Other temporal and geochemical considerations seem to determine whether the closed basin sediments ever received lithium-enriched fluids, and whether lithium was retained in the sediments.

II. Hydrothermal or ground-water leaching silicic volcanics (air- and waterlain ashes, welded tuffs, rhyolites) in the basin or on its margins

Lithium can be leached by fairly low-temperature (120°C) alkaline fluids from rhyolitic-composition glasses in the laboratory. In nature, the lithium-rich clays found so far seem to occur in proximity with caldera complexes (Glanzman, McCarthy, and Rytuba, 1978) and/or areas of rhyolitic volcanism less specifically identified (Brenner-Tourtlot, 1979). These highly reactive silicic and peralkaline volcanics may have been derived from fractionated magmas higher in such lithophilic elements as Li, Be, B, and U. Hydrothermal activity is common in such volcanic terrains, and signs of its activity vary from calcareous tuffa mounds, siliceous sinter, lacustrine oncolitic cherts, spring pots, and

stromatolites, to more pervasive, invasive signs such as extensive silicification of ashes and other sediments along faults, and argillization, zeolitization, and feldsparization of sediments across facies boundaries. In cases noted so far, areas of intense alteration within a basin are least likely to contain anomalously high lithium values in altered ashes and clays; lithium's extreme solubility and mobility (due to its tight binding to waters) drives it from centers of extensive alteration to areas of less intensive alteration.

III. Evaporative concentration of lithium-enriched fluids within the basin

The Basin and Range Province, the Rio Grande Rift, and its closed-basin precursors (Brenner-Tourtlot and Machette, 1979), and the various caldera complexes related to these extensional features are Tertiary and younger, and have been characterized by generally arid to semiarid climates. These climatic conditions have served not only to concentrate lithium-enriched fluids, but to provide concentrations of other ions necessary for creating smectites that can hold lithium as interlayer cations (dioctahedral smectites) or as part of the octahedral structure (trioctahedral smectites such as hectorite) of clays.

Evidence of siliceous cementing of ashes (suggesting pH's >8.4), gypsum cement and interbeds, saline minerals, primary dolomite deposition, and cement, (limited) zeolitization of ashes, algal stromatolites, and red beds all point toward evaporative concentration as a method of enrichment of lithium. Some of these factors are indicative of fairly shallow and(or) ephemeral alkaline and saline lacustrine conditions also. Because lithium is not known to form salts in nature, but must be incorporated (with its waters), into the structures of salines, or as cations into the interlayers of neoforming smectites, it is imperative that lithium-enriched fluids be evaporated to dryness; the deep saline lake might never deposit its lithium fraction.

The role of evaporative concentration can be seen today in Pleistocene to Holocene playa sediments that contain up to 1,700 ppm Li (Vine, 1980, p. 19), and show no signs of hydrothermal alteration, just traces of gypsum, halite, dolomite, and abundant calcite in a matrix of nonashy lacustrine dioctahedral smectites. It apparently requires the reactive chemistry of ashes and the (hydrothermal?) leaching of another rhyolitic body or those ashes farther away, plus evaporative concentration to produce lithium-rich clays with as much as 5,200 ppm Li (Brenner-Tourtlot and Glanzman, 1978).

IV. Temporal and diagenetic factors

The relative scarcity of lithium-enriched clays may reflect the degree of dryness (hence, incorporation into the altered-ash smectite structure) the basin fluids achieved before breaching of the basin. The catchment area, rainfall and evaporation rates, and the rate of sedimentation and diagenesis in the basin would determine the permanence and salinity and alkalinity of the water table within a closed basin. Too-early breaching (such as seen at Long Valley caldera) could allow

lithium-enriched fluids to escape to a lower basin (Searles Lake) where further evaporative concentration might take place (Smith, 1976, p. 92-93).

The final degree of diagenesis and hydrothermal alteration also determines how much lithium can be incorporated into altered ashes and clays. For instance, Creede caldera moat-fill sediments and ashes are altered rather completely to clinoptilolite, and contain only background amounts of lithium (<150 ppm). Alteration must leave a goodly amount of smectite in the ashes as the basin proceeds to dryness for suitable sites in the neoforming clays to occur. Hence, extremely high alkalinities and salinities are not favorable. Likewise, total zeolitization and feldspathization are contraindicative.

V. Elements related to lithium occurrence

If, indeed, lithium is freed from highly silicic volcanics by either ground-water or hydrothermal action, there are other cations we might expect to see as co-travellers within the closed basins. The lithophilic U, Be, B, and F have all been noted as being found in anomalous concentrations to mineable quantities in closed basins that contain anomalous lithium-rich clays (Glanzman, Rytuba, and Otton, 1979, and Lindsey, 1979). Hg and Mn have been noted also (Rytuba and Glanzman, 1979, and Brenner and Glanzman, 1979); their less obvious geochemical link may suggest that nearby high lithium concentrations are the result of remobilization of existing lithium in those sediments rather than addition of lithium at the same time as the Hg and Mn.

What Do Lithium-Rich Clays Look Like? How Much Lithium Does A Clay Need To Be Considered A Possible Future Resource? What are Effective Prospecting And Analytical Techniques?

Unfortunately, lithium-rich clays look like any other smectite; there are no characteristic colors or mineral assemblages unique to lithium content visible in the field. Thus it helps to know what any smectite looks like. These clays, regardless of their lithium content, are the puffy, popcorn-weathering clays formed by expansion upon wetting, and the lack of contraction of the clay structure upon drying. They are extremely "greasy" when wet. They vary from brilliant white to pastels to dark-greens and browns, and often reflect the amount and oxidation state of iron-containing contaminants. If the smectites reflect the addition of primarily pure ash to a section, the bed may stand out as much more puffy or of a different color than the also-smectitic playa clays within the section. If the lacustrine clays themselves contain the lithium, or if the ash is more comminuted or altered, detection of more smectitic beds can be more difficult.

The various platy, lathlike, and fibrous zeolites often occur in altered ash beds whose smectite content remains high enough to contain anomalous lithium. Zeolite content can be indicated by conchoidal fracture across sedimentary structures, and the "punky" dull hollow sound a hammer makes striking the rock. Presence of zeolites does not guarantee anomalous lithium, but may indicate that diagenetic geochemistries were favorable for its incorporation.

Thus, hunting for lithium-bearing clays requires extensive collecting in the field, because its presence cannot be detected without later chemical analysis. Collect from ashy horizons and(or) smectitic and zeolitic-clays. Collect from fine-grained beds in proximity to, and moving away from, spring or fault features, especially if they were penecontemporaneous with deposition. Be suspicious of clays that become gel-like when wet.

X-ray diffraction and semiquantitative spectrography are two valuable first diagnoses for lithium content of fine-grained sediments you have collected. If the XRD whole-rock traces shown abundant smectites, either di-or trioctahedral, and SQS shows lithium values greater than 300 ppm, you've found a lithium-enriched clay. Values of 6,800 ppm and higher have been reported from whole-rock analyses of a gel-like lacustrine clay from the moat-fill of McDermitt caldera (Rytuba and Glanzman, 1979); the U.S. Bureau of Mines is learning ways to extract the lithium, and may eventually find a way to make this process market-competitive.

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BEDDED BARITE

By
Keith B. Ketner

Appearance

Bedded barite looks like the sedimentary rocks with which it is associated. It is thin bedded, dark colored in shades of gray, like bedded chert, shale, or argillite, and breaks into platy fragments along shaly interbeds. The experienced observer however notes that barite sparkles a little in the sun whereas the associated rocks are commonly uniformly dull. On close inspection, barite is seen to be locally coarsely granular and to include blades and rosettes in contrast with the uniformly fine-grained associated siliceous rocks.

Geographic Extent

Bedded barite deposits are known principally in Nevada and Arkansas, but are also present in Idaho and Washington.

Stratigraphic Range

Most deposits are in Devonian rocks, but they are known to occur in Cambrian, Ordovician, and Lower Mississippian rocks as well. Economically insignificant deposits have been found in Silurian rocks. As exploration proceeds, the known stratigraphic range of deposits increases.

Nature of Enclosing Strata

Almost all known bedded barite deposits are in sequences composed primarily of well-bedded siliceous rocks such as shale, argillite, chert, siltstone, and sandstone. However, a few, such as those in the Cambrian Preble Formation and the Ordovician Comus Formations of north-central Nevada are in sequences that include a large proportion of carbonate rocks. In both of these formations the barite is more closely associated with carbonate than with the siliceous rocks.

Depositional Environment of Enclosing Strata

Rocks containing bedded barite were deposited in a wide variety of environments. The Cambrian Preble Formation represents an outer shelf environment. The part of the Ordovician Comus Formation that includes barite deposits is conglomeratic oolitic dolomite suggestive of a very shallow water, near-shore environment. Most Devonian rocks, such as the Slaven Chert, that contain bedded barite are rich in bedded chert--a type of rock that represents intervals when little or no detrital or carbonate sediments were being deposited. The precise conditions of water depth and distance from shore are poorly understood, however. In sharp contrast, Mississippian flysch deposits in which barite is found in both Nevada and Arkansas are detrital sequences that represent rapid accumulation of siliceous sediment. Lower Mississippian units in Nevada and the Stanley Shale in Arkansas are formations of this type.

Mode of Origin

The origin of bedded barite, like that of most other stratabound deposits, is unsettled and controversial. Theories range from primary deposition as a marine sediment to epigenetic hydrothermal replacement (Shawe, Poole and Brobst, 1969; Ketner, 1963).

Exploration Techniques

First, locate favorable terranes by means of geologic maps and descriptive reports. As presently understood the favorable terranes would be Paleozoic siliceous rock sequences such as chert, shale, argillite, siltstone, and sandstone around the borders of the continent. The chert, shale, and argillite should be dark gray, not green, but the siltstone and sandstone can be light colored. Second, traverse these terranes at close intervals while constantly picking up pieces of float and knocking off pieces of outcrops. The specific gravity or "heft" of these rock fragments is the first screening test to determine whether they are barite or not. If the rock is distinctly heavier than ordinary rock and if it breaks easily with a hammer, the next step is examination with a hand lens. If cleavages, blades, or rosettes are observed, the rock is probably barite.

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BEDDED BARITE

By

F. G. Poole, D. R. Shawe, R. O. Rye, and G. A. Desborough

Regional setting

Throughout the world, bedded barite (BaSO_4 , barium sulfate) of commercial grade (>4.0 G.) generally occurs in Phanerozoic (chiefly Devonian) eugeosynclinal siliceous rocks within orogenic belts accreted to continental margins. Most bedded barite is intercalated with chert and (or) mudstone units or related oceanic facies whose deposition predated orogenic deformation.

Description of baritic rocks

On outcrop, the beds of barite occur as lens- and tabular-shaped bodies as thick as 15 m and as broad as 1.5 km. Laterally most beds pinch and swell and commonly are discontinuous and podlike owing to folding and faulting.

Bedded barite occurs as four basic types: (1) laminated barite with anhedral and tabular crystals <0.1 mm in size; (2) rosette barite composed of spheroidal masses that consist of crystalline blades 0.1 to 15 mm in size commonly radiating from a nucleus; (3) conglomeratic barite with the matrix composed of types 1 and 2; and (4) barite crystals forming cement in sandstone and siltstone. Types 1 and 2 are the most common and have the highest purity. Sparse to abundant rosettes occur both in the relatively pure fine-grained barite beds as well as in impure beds composed of chert, mudstone, and siltstone. Conglomeratic barite generally contains intraformational clasts of granules, pebbles, and cobbles of chert, mudstone, siltstone, barite, volcanic rock, barite rosettes, and phosphatic nodules all set in a fine-grained matrix of barite. Baritic siltstone, sandstone, and conglomerate beds are sparse. Crystalline barite occurs as cement between grains where quartz and feldspar sand and silt make up a major part of the rock.

Laminated beds of unaltered fine-grained and coarsely crystalline rosette barite are dark gray in color; slightly altered barite is medium gray; moderately altered is light gray; and intensely altered is white. Unaltered to moderately altered barite is sugary textured and has a fine grain size whereas intensely altered barite has a medium to coarse grain size. Intensity of gray depends upon the amount of organic matter in the rock, which commonly ranges from 0.1-0.5 weight percent organic carbon in dark-gray barite to <0.1 in white barite. As the rock is heated during burial or from an external heat source, the organic material is distilled and the rock becomes lighter gray and ultimately white.

Genesis

Genetic models for bedded barites fall into two opposing schools of thought: (1) syngenetic-diagenetic sedimentary origin (Zimmernan and Amstutz, 1964; Shawe, Poole, and Brobst, 1969; Brobst, 1973; Rye, Shawe, and Poole, 1978) and (2) epigenetic replacement origin (Scull, 1958; Ketner, 1963; 1965; 1975).

Sedimentary features and fossils--Textural, structural, and paleontological features indicate a sedimentary origin for most bedded barite. Wavy laminae of barite, chert, and mudstone are parallel, graded bedding is present, and barite laminae adjacent to many clasts, nodules, and barite rosettes are draped around the bodies indicating the presence of the barite before compaction of the sediment. Intraformational conglomerate with clasts of barite, including fragmented rosettes, chert, mudstone, siltstone, volcanic rock, and phosphatic nodules set in a fine-grained barite matrix indicates submarine erosion and redeposition during barite sedimentation. Sandstone and siltstone beds with barite cement indicate migration and precipitation of barite from fluids rich in barium sulfate during diagenesis.

Megafossils occur as molds and casts in fine-grained barite. They include pelmatozoan columnals and brachiopod shells. Microfossils include sponge spicules and radiolarians. Barite has selectively replaced the silica in these microfossils.

Stable isotope data--Stable isotopes of sulfur indicate a syngenetic and diagenetic origin for most bedded barite. $\delta^{34}\text{S}$ values of laminated fine-grained barite in the Devonian Slaven Chert range from about 21 to 29 permil, with most values near 25 permil (Rye, Shawe, and Poole, 1978). The average value of about 25 permil is typical of Upper Devonian marine sulfate which is the age of the Slaven Chert facies in Nevada that contains most of the bedded barite that has been sampled and analyzed. Although both the sulfate and barium must have come from the Paleozoic ocean, the ultimate source of the barium is not clear. Spatial association of modern barium-rich sediment with the East Pacific Rise suggests a possible spreading-center source for barium. The fact that $\delta^{34}\text{S}$ values of the laminated fine-grained barite vary almost 8 permil suggests that either bacteria and (or) mixing of sulfur from two sources was locally involved in barite deposition and diagenesis. The initial sedimentary $\delta^{34}\text{S}$ values of the laminated fine-grained barite were apparently retained during recrystallization and the loss of organic carbon associated with hydrothermal alteration. Barite rosettes and concretions and barite cement in sandstones and siltstones have $\delta^{34}\text{S}$ values ranging from about 29 to 56 permil, suggesting that they formed in a partially closed system either on the ocean floor or within the sediments where bacterial reduction of seawater sulfate occurred (Rye, Shawe, and Poole, 1978).

Conclusions--Sedimentary features, fossils, and stable isotopes of sulfur all indicate a syngenetic and diagenetic origin for most bedded barite. There is evidence of barite diagenetically replacing minor amounts of earlier minerals. Coarsely crystalline white barite veins crosscut fine-grained gray barite beds and some features indicate epigenetic replacement, recording postdepositional mobilization of some barite.

Prospecting techniques

Exploration strategy for discovery of bedded barite deposits should consider the following geologic factors:

- (1) Most commercial-grade (4.1-4.4G.) barite occurs as beds within Paleozoic eugeosynclinal siliceous facies, particularly Devonian rocks;
- (2) Sedimentary strata of baritic eugeosynclinal rock terranes contain anomalously high concentrations of barium;

- (3) From a distance, thick beds of relatively pure barite are devoid of vegetation and look like limestone and dolomite beds;
- (4) Closeup, barite is soft (3H) and can easily be scratched with a hammer or knife, will not react with dilute HCl acid, and has an appreciably higher bulk rock density than limestone or dolomite; most bedded barites contain distinctive rosettes;
- (5) Talus slopes beneath outcropping large barite deposits contain gray, fine-grained heavy rock and barite rosettes;
- (6) Bedded metal sulfides in places are associated with bedded barite in eugeosynclinal rocks; therefore, if bedded metal sulfides are in the area, it is likely that bedded barites are there also.

Potential resources

Undiscovered deposits (speculative resources) of bedded barite remain large. Additional commercial deposits will be found principally in dark-colored Paleozoic eugeosynclinal siliceous facies in orogenic belts. These belts should be primary targets for exploration in sedimentary rocks throughout the world.

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GREAT BASIN PHOSPHATE

By
Keith B. Ketner

The principal phosphate deposits in the Great Basin are sedimentary rocks that occur in marine sequences of Mississippian and Permian ages. Although these deposits are locally rich enough to compete with phosphate commercially exploited from other regions, their exposures tend to be too thin and too small in extent to be presently mineable. Their potential lies in the future when demand presumably will be greater, supplies smaller, and prices higher.

Phosphate deposits of Mississippian age occur in Utah and they may extend a short distance into Elko and White Pine Counties in northeastern Nevada. These deposits are confined to the middle part of the Mississippian System where they form the basal beds of three laterally equivalent formations: the Deseret Limestone, the Woodman Formation, and the Chainman Shale. Outcrops of these units are shown on the geologic maps of northwestern and southwestern Utah (Stokes, 1963; Hintze, 1963). The Chainman Shale is shown on the Preliminary Geologic Map of Elko, County, Nev. (Hope and Coats, 1976) and map units designated MD and MDd that include the Chainman are shown on the Geologic Map of White Pine County, Nev. (in Hose and Blake, 1976).

Phosphate deposits of Permian age occur in northwestern Utah and northeastern Nevada. The deposits are confined to the upper parts of the Permian sequences where they constitute parts of the Park City Group (or Formation), the Phosphoria Formation, and the Plympton Formation. Outcrops of these stratigraphic units are shown on the geologic maps of northwestern and southwestern Utah, the Preliminary Geologic Map of Elko County, Nev., and the Geologic Map of White Pine County, Nev.

Richly phosphatic beds, called phosphorite, constitute a small part of the above mentioned formations. Consequently, when the formations are located on the ground with the help of geologic maps, a search must be made for the phosphorite beds. Unfortunately, phosphorite breaks down easily during weathering and rarely forms natural outcrops. The presence of phosphorite beds concealed by soil is commonly indicated by chips of phosphorite and phosphatic chert lying on the surface of the ground over the trace of phosphorite bedrock or downslope from it. The phosphorite chips range in color from tan to dark-brown or black and on close inspection commonly are seen to be partially coated with a dull-bluish-white film or "bloom" formed by exposure to the atmosphere. Commonly phosphorite is composed partly of rounded particles and phosphatic fragments of the skeletons of marine animals such as the shells of clams, snails, and bryozoa or sea moss. These components can usually be seen with the naked eye and are quite apparent when examined with the aid of a 10x magnifying glass.

When the phosphorite beds are located they must be exposed by trenching across the strike of the beds for the purpose of sampling and measurement.

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HIGH-GRADE SILICA DEPOSITS

By
Keith B. Ketner

By "high grade" is meant silica deposits that are naturally pure enough to be used, without complex and expensive beneficiation, as the raw material for manufacturing such products as photovoltaic cells, quartz crystals, and top quality glass. Such uses demand no more than a trace of aluminum, iron, chromium, nickel, copper, cobalt, phosphorous, and boron.

Historically, much high grade silica has been obtained from quartz or quartzite cobbles in gravel; quartz crystals in veins; and quartz crystals and massive quartz in pegmatites. Such deposits are relatively small, are being rapidly depleted, and require labor-intensive mining and beneficiation procedures. Eventually all high-grade silica will be obtained from sedimentary deposits of sand, sandstone, and quartzite, for these are the only suitable inexhaustible sources available.

The quartzite formation with the highest known content of silica and the lowest known content of deleterious trace elements is the Eureka Quartzite and its correlatives of Ordovician age. This formation crops out sporadically in the western states from central Idaho through western Utah and eastern Nevada to southeastern California. The Eureka averages about 300 feet in thickness and commonly most of this thickness is solid, pure quartzite free from carbonate cement or interbeds of shale or carbonate.

The loosely consolidated sandstone with the highest known content of silica and the lowest known content of deleterious material is the St. Peter Sandstone and its equivalents of Ordovician age. This formation crops out over broad areas in the Mississippi Valley from northern Minnesota and Wisconsin through eastern Iowa, western Illinois, eastern Missouri, and northern Arkansas to central Oklahoma. Its average thickness is between 200 and 300 feet and most of this thickness is free from interbeds of nonquartz material. The St. Peter breaks down readily to loose sand and therefore can be mined by hydraulic methods and washed to remove non-quartz stains and coatings.

A few other extensive formations that rival the Eureka and St. Peter in purity are known but none are quite so ideally pure. The Tuscarora Quartzite and equivalents of Silurian age in the Appalachian region is locally nearly as pure as the Eureka Quartzite and is more conveniently located with respect to industrial centers. The Oriskany Sandstone and its equivalents of Devonian age in the Appalachian region is locally almost as pure as the St. Peter Sandstone but many of the exposures are too firmly cemented to be mined by hydraulic methods and are not therefore amenable to beneficiation by washing. Some of the better exposures of the Oriskany are in urban or agricultural areas where mining is not feasible and most of the best exposures of the formation have been mined out.

Geologic maps, especially State Geologic Maps, are the best guides to the general location of high-grade silica deposits. Information on the Eureka and St. Peter have been compiled from geologic maps and reports and summarized in two recent publications (Ketner, 1976; 1979). Information on the location of outcrops of the Tuscarora and Oriskany can be obtained from the State Geologic

Maps of New York, Pennsylvania, Maryland, New Jersey, West Virginia, Virginia, and Tennessee. Information on the general locations of other stratigraphic units, locally of high but not highest quality, is given by Murphy (1960).

A logical procedure for exploration would be to plot the exposures of the above formations and others thought to be of suitable quality; select areas of exposure that are well placed with respect to transportation and markets; and finally sample and test the silica deposits within those areas for the best chemical and physical attributes.

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NEW YORK TALC

By
C. E. Brown

Regional Setting

White talc-tremolite schist occurs as a metasedimentary unit in a thick sequence of mainly dolomitic and Ca-Mg silicate-rich marbles of Proterozoic age. They are included in the Grenville complex in the Grenville lowlands of St. Lawrence County, N.Y. In the mining district, the sequence is folded into a doubly plunging synform that is overturned to the southeast and the ore zone is locally thickened.

Deposit Characteristics

Talc-tremolite schist occurs in a layer of variable thickness from 500 to a few feet thick. Thickness varies with changes in trend because of warping and refolding of the major fold. Deposit is layered and adjacent layers vary mineralogically. Underlying rock is a thinly interlayered zone of quartzite and tremolite layers and below that is dolomite with thin parallel lensy layers of Ca-Mg silicates. Overlying rock is dolomitic marble.

Mine/Outcrop Characteristics

Ore zone locally forms low outcrops because zone is made up of insoluble silicate minerals in a carbonate terrane. Wherever glacial direction is close to the trend of the unit, glacial scour has lowered the ore zone (because of its softness) below surrounding marble. There the ore zone is represented on the surface by a flat, filled valley.

The ore zone is made up of a layered sequence of rocks composed of combinations of talc, tremolite, anthophyllite, serpentine, and minor carbonate in various ratios. Although the talc-tremolite schist occurs within tens to hundreds of feet of the very pyritic, zinc, ore bodies of the Edwards-Balmat area, no sulfides occur in the talc ore, nor can they be tolerated in the product.

Genesis

The protolith for tremolite schists is siliceous dolomite. In order to have talc and anthophyllite included, one or combinations of three situations had to occur. These are: (1) some calcium must be removed, (2) magnesium was added by metasomatism, (3) original rock had excess magnesium probably in the form of magnesite. Of course, CO₂ also had to be removed to result in a complete silicate assemblage.

Deposition of these sediments was in an environment in the Proterozoic that was producing much dolomite with silica, possibly as chert. A thick unit of anhydrite that occurs nearby in the sequence indicates an evaporitic environment of deposition. Such an environment also might have excess magnesium being deposited in some strata as magnesite, and, although magnesite has not been identified here, I lean toward this genesis for the talc-tremolite zone.

Amphibolite facies metamorphism converted dolomite-magnesite-silica to tremolite-diopside-anthophyllite. Retrograde processes formed talc-tremolite-serpentine-anthophyllite that is the ore.

Prospecting Techniques

Map out carbonate sequences in metasediments. Look for dolomitic marble with segregations of silicates (diopside-tremolite-talc-serpentine). Decipher stratigraphic sequence and look for zones of talc-tremolite without quartz and carbonate. These may show up as a ridge where weathering is mainly a chemical process or as a consistent low area where weathering is mainly mechanical.

Economics

Talc-tremolite has many uses, mostly as a ceramic base and as a paint extender. Other uses are as a white filler in plastic, rubber, floor covering, sealants, electrical insulation, paper, and many more.

All uses depend on whiteness and inertness. For a ceramic base, ore must be white after firing. For paint it must grind easily to micron sizes and must have low oil absorption.

Ore must have a very low manganese content, contain no quartz, and for many uses, low carbonate. High calcium is acceptable in some products.

Grade and use of ore is determined by several physical tests and some chemical tests. Zones of different mineralogic composition are mined selectively for the product desired.

Grinding and mixing are the main milling processes. Flotation might be feasible, if sulfides are present.

Fibrous mineral content at one time was an asset and now is carefully controlled because of environmental health considerations.

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MODEL FOR ZEOLITES IN SALINE, ALKALINE-LAKE DEPOSITS

By

Richard A. Sheppard

Introduction

Zeolites are crystalline hydrated aluminosilicate minerals of the alkali and alkaline-earth elements. They have an infinitely extended framework structure that encloses interconnected cavities occupied by the relatively large cations and water molecules. The cations are chiefly monovalent sodium and potassium and divalent calcium and magnesium, but divalent barium and strontium are essential constituents of some natural zeolites. Most natural zeolites show considerable ranges in chemical composition, including ranges in the water content, the cation content, and the Si:Al ratio. The indices of refraction and specific gravity of zeolites are notably low, being in the range of 1.46-1.52 and 2.0-2.3, respectively. Hardness is about 3.5-5.5.

In the last 20 years or so, it has become apparent that zeolites are among the most common authigenic silicate minerals in sedimentary rocks. The zeolites occur in sedimentary rocks that are diverse in lithology, age, and depositional environment (Hay, 1966). More than 40 distinct species of zeolites are recognized, but only about twenty have been reported from sedimentary rocks. Of these, only six are common in saline, alkaline-lake deposits; they are analcime, chabazite, clinoptilolite, erionite, mordenite, and phillipsite. The zeolites in sedimentary rocks are finely crystalline; deposits of this type are voluminous and have economic potential for many industrial and agricultural processes.

Geologic Setting

Zeolites occur in sedimentary rocks from a variety of geologic settings, but this model will apply only to the closed hydrographic basin or the commonly termed "saline, alkaline-lake deposit". Most zeolites in sedimentary deposits formed after burial of the enclosing sediments by the reaction of aluminosilicate materials with the pore water. Silicic volcanic glass is the aluminosilicate material that most commonly served as a precursor for the zeolites, although materials such as clay minerals, feldspars, feldspathoids, and gels have also reacted locally to form zeolites. Thus, the closed-system zeolite deposit is generally the result of the diagenetic reaction of volcanic glass with connate water trapped during sedimentation in a saline, alkaline lake.

Tectonic Setting

Most closed hydrographic basins are situated in either block-faulted terraines, such as the Basin and Range province of the western United States, or trough valleys associated with rifting, such as the East Rift Valley of Kenya. In both types, only a limited amount of clastic debris reached the lake (Surdam and Sheppard, 1978).

Brine Evolution and Composition

Saline, alkaline lakes are commonly of the sodium carbonate- bicarbonate variety and have a pH greater than 9, accounting for the relatively rapid solution of vitric material and precipitation of zeolites. The delicate imbalance between precipitation and evaporation causes the fluctuations in lake level and salinity. Lakes lacking outlets or lakes in closed hydrographic basins are common in arid or semiarid regions where the annual evaporation exceeds rainfall. Not all lakes in closed basins are saline and alkaline; some are just saline, such as the Great Salt Lake. A closed basin surrounded by igneous and metamorphic rocks or by sedimentary rocks other than pyritic shales and marine evaporites is an ideal setting to develop a saline, alkaline lake. Lakes in closed basins commonly are characterized by a systematic change from fresh water to saline, alkaline brine from shore or points of discharge to the basin center.

Mineral Zones

The most distinguishing feature of zeolites in saline, alkaline-lake deposits is the lateral zonation of minerals. Fresh glass occurs along the margin and at inlets of the ancient lake. The glass is succeeded basinward by a zone of zeolites and then, in the central part of the basin, by potassium feldspar. This pattern of lateral zonation applies to a single tuff bed as well as to the entire lacustrine deposit. The tuffs of Pleistocene Lake Tecopa in southern California exemplify this pattern (Sheppard and Gude, 1968). The zeolites at Lake Tecopa are chiefly phillipsite, erionite, and clinoptilolite.

Some deposits of saline, alkaline lakes show a variation in the above zonal pattern. An additional zone of analcime may occur between the zeolite and potassium feldspar zones. This pattern has been recognized in the Miocene Barstow Formation of southern California (Sheppard and Gude, 1969), the Pliocene Big Sandy Formation of western Arizona (Sheppard and Gude, 1973), and the Eocene Green River Formation of Wyoming (Surdam and Parker, 1972).

Field Characterization of Zeolitic Tuffs

Prospecting for bedded zeolite deposits is difficult because the zeolites are finely crystalline and resemble bedded diatomite, feldspar, or bentonite in the field. Zeolitic tuffs generally have an earthy luster and are resistant. Although some are pastel shades of yellow, brown, red, or green, many are white or light gray. The zeolitic tuffs are ledge forming, particularly in arid areas. Zeolitic tuffs generally lack the "pop corn" coating that is characteristic of bentonites. The tuffs range in thickness from less than a centimeter to several meters. Original textures and sedimentary structures, such as ripple marks, are generally preserved in the zeolitic tuffs. X-ray powder diffraction analysis of bulk samples is the commonly used technique to determine the abundance and identification of the zeolite and associated minerals.

Other Criteria to Help Locate Zeolites

The initial guide to the location of this type of zeolite deposit is the recognition of the lacustrine strata, or more importantly, strata of a saline lake. Rather than repeat the criteria useful in prospecting for nonmarine saline deposits, the reader is referred to the excellent review by Smith (1966). Certain features, however, deserve emphasis: (1) occurrence of bedded saline minerals, such as trona, nahcolite, and halite; or the occurrence of disseminated crystal molds of saline minerals such as gaylussite or pirssonite; (2) dolomitic mudstone; (3) chemical deltas; (4) strand-line deposits, such as algal stromatolites, oolites, and ostracode lag deposits; (5) presence of certain associated minerals, such as searlesite, dawsonsite, fluorite, barite, celestite, and strontianite; and (6) occurrence of Magadi-type chert.

The absence of certain features can be indicative of a saline, alkaline environment. The distribution of fossils can indicate abnormal salinity. Fresh-water diatoms and ostracodes may occur in sediments near the inlets of the lake, but away from these areas, there is an absence of fossils. Both kaolinite and vitric material are unstable in the brine of saline, alkaline lakes; thus, these materials survive only in the marginal parts of the lake that received a continual supply of fresh water. Certain calcic zeolites, such as laumontite and wairakite, have not been reported from saline, alkaline-lake deposits.

Although zeolites have been reported from saline, alkaline-lake deposits as old as late Paleozoic, most deposits are Cenozoic. Zeolites are relatively unstable silicate minerals; and with an increase in age, temperature, pressure, or depth of burial, the zeolites are transformed to other mineral phases.

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DEPOSITIONAL MODEL FOR BEDDED SODIUM CARBONATE DEPOSITS

By
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Introduction

Although natural occurrences of sodium carbonate are known from many parts of the world, economic deposits are rare. In the United States, 91 percent of the soda ash (Na_2CO_3) production is from two natural sources: the bedded trona deposits of the Tertiary Green River Formation in southwestern Wyoming and brines from Pleistocene Searles Lake, California (Kostick and Foster, 1979). Significant production from natural deposits elsewhere in the world include Lake Magadi, Tanzania, and Lake Texcoco, Mexico (Mannion, 1975, Tables 1 and 4). Solvay plants currently produce about 80 percent of the world's supply of soda ash. In view of construction costs, and the increasing concern with environmental problems of disposal of wastes from Solvay plants, the impetus for exploration for natural deposits of sodium carbonate should increase in the future. The potential for discovery of new deposits of sodium carbonates seems good.

Good setting

Sodium carbonate deposits are restricted to continental rocks. Most deposits originate in closed lacustrine basins with a semi-arid or arid climate where evaporation exceeds precipitation. Salts may be deposited in shallow ephemeral playas whose lake waters evaporate seasonally to dryness or, in exceptional cases, in a closed lake with a permanent body of saline water during evaporative stages of the lake. The largest deposits known (i.e., the trona and nahcolite deposits in the Green River Formation of Wyoming and Colorado) were deposited under the latter conditions.

Unlike marine evaporite basins which are supplied largely from an oceanic reservoir of known composition, the composition of waters of a closed lake is determined largely by the rocks exposed in the drainage basin of the lake. The exposed rocks may be of one or more types. Air-fall tuffs may contribute large amounts of dissolved and detrital sediment during periods of volcanic activity. The lake may be supplied by waters from a single topographic basin, or from a drainage system that flows through several basins, giving rise to a chain of lakes. Ground waters carrying large quantities of solutes may find their way into closed lake basins via seeps and springs.

In view of the many possible combinations of size, shape, and depth of the lake basin; subsurface hydrologic systems; ephemeral- or permanent-lake regimes; and the composition of the source rocks in the hydrographic basin, the sediments including saline assemblages deposited in closed lakes are highly varied and complex.

Depositional constraints

When the salting stage of a perennial closed lake is reached, - precipitation may be expected to occur in the topographically lowest part of the lake basin, identified herein as the chemical depocenter. The chemical depocenter may remain stationary through time, or it may migrate to different parts of the basin in response to changes in sediment distribution patterns, climate, and tectonic activity in the basin. The distribution, thickness, and grade of the evaporite deposits would be affected accordingly.

The structurally deepest part of the basin may not necessarily coincide with the chemical depocenter, but depending on its location in the basin, the structural low may be the site for accumulation of dominantly clastic sediments, whereas the topographic low point of the lake basin and its accumulating evaporites may be located elsewhere. Favorable structural conditions for deposition of thick sequences of evaporites are (1) a gradually subsiding basin that can accommodate thick sequences of sediment, and (2) a basin asymmetry that favors a pronounced topographic deep that can maintain a permanent body of water for a substantial length of time. Such conditions seem to have prevailed during deposition of trona and nahcolite in the Green River Formation in Wyoming and Colorado.

Areal zonation of evaporites

Syngenetic minerals in marly sediments of closed-lake basins commonly show areal and vertical zonation. During evaporative lake phases, the more soluble salts tend to migrate toward the chemical depocenter and precipitate when the lake and sediment waters exceed saturation for a given salt.

A typical lateral sequence of syngenetic carbonate and chloride minerals in lacustrine sediments from basin edge to center in the Green River Formation is:

calcite-----dolomite-----shortite-----trona/nahcolite-----halite
(Ca) (Ca,Mg) (Ca,Na) (Na) (Na) (Na)

In this sequence, the less soluble alkaline earth carbonates give way basinward to sodium carbonates and halite. Sulfo-carbonate minerals may show similar zonation, such as observed in carbonate muds in Deep Springs Lake, California (Jones, 1965, fig. 2):

calcite (aragonite)-----dolomite-----gaylussite-----thenardite-----
burkeite
(Ca) (Ca) (Ca,Mg) (Ca,Na) (Na) (Na)

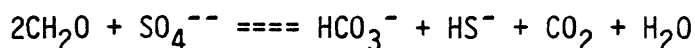
Associated with burkeite at the saline depocenter are trona, nahcolite, and halite. Authigenic silicate minerals may show similar zonation.

Areal zonation of the minerals in the above examples form a series of overlapping, rather than separate, bands outward from the basin center. Recognition of areal zonation of syngenetic minerals in closed-basin sediments may be a useful guide in exploring for sodium carbonate deposits.

Chemical constraints

The most common ions in surface waters feeding closed lakes are Ca, Mg, Na, (HCO₃ + CO₃), SO₄, and Cl. High-purity sodium carbonate deposits require parent waters that become ultimately enriched in sodium and carbonate and deficient in Ca, Mg, SO₄, and Cl so that Na >> (Ca + Mg) and (HCO₃ + CO₃) >> (SO₄ + Cl). The ratio Na:Cl must exceed unity. Early precipitation of alkaline-earth carbonates (calcite, dolomite, etc.) can explain the enrichment of Na relative to (Ca + Mg) in the evolution of lake brines. However, the increase of (HCO₃ + CO₃) relative to (SO₄ + Cl) is less obvious. Sulfate must be either deficient in the waters feeding the lake, such as observed in volcanic and metamorphic terranes as described by Jones (1966) and Garrells and Mackenzie (1967), or it may be removed by partial to complete reduction to sulfide species (H₂S, HS⁻, and S²⁻) as suggested in a depositional model for Green River evaporites proposed by Dyni (1981). The reduced sulfur species can react with available dissolved iron at low Eh to precipitate as iron sulfide, or it can escape to the atmosphere as H₂S.

The only known process of sulfate reduction at ambient temperature and pressure in the lacustrine environment is by sulfate-reducing bacteria according to the following generalized reaction:

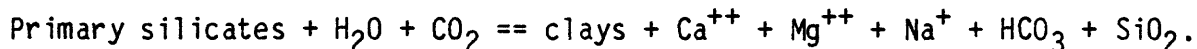


"Organic bacterial
matter" enzymes

If sodium becomes the dominant cation in an evolving closed-basin alkaline brine in which sulfate reduction is quantitatively important, significant amounts of bicarbonate ion may be produced in order to maintain electrical neutrality with sodium ion in the water.

Organic matter required in the above reaction may be largely the decomposition products of algae, bacteria, and humic material that are metabolically assimilable by sulfate-reducing bacteria. Warm alkaline barines can produce prodigious quantities of aquatic micro-organisms that could sustain high rates of sulfate reduction. Therefore, organic-rich alkaline waters in a closed-lake regime may be a particularly favorable environment for sodium carbonate accumulation even in the presence of abundant introduced sulfate.

Hydrolysis of silicate minerals in source rocks of the drainage basin as well as in the lake sediments, may also contribute significant quantities of bicarbonate as shown by the following schematic reaction:



Since the solubility of sodium carbonate minerals such as trona and nahcolite is less than that of halite, a horizontal salinity gradient in the lake brine would favor differentiation of these salts during salting stages. Thus, the grade of the sodium carbonate resource would be expected to be increased, especially in a larger perennial lake in which horizontal salinity gradients are strong.

The sodium carbonate deposits of the Green River Formation contain many beds of relatively pure trona that grade laterally into mixed halite and trona toward the basin depocenter of the Green River Basin in southwestern Wyoming (Burnside and Culbertson, 1979). Similarly, beds of nahcolite in the same formation grade laterally into mixed halite and nahcolite toward the depocenter in the Piceance Creek Basin in northwestern Colorado (Dyner, 1974). Differentiation of these evaporites was probably made possible by strong horizontal salinity gradients in the lake brines.

Exploration guides

The known occurrences of sodium carbonate are Tertiary and Pleistocene in age; pre-Tertiary deposits are unknown. The most promising areas for exploration for sodium carbonate deposits would appear to be those underlain by lacustrine rocks of Cenozoic age that were deposited in endorheic regions of the world. In the United States, the Basin and Range Province of the Western Interior is such a region that appears to have good potential for discovery of sodium carbonate deposits in addition to those already known.

Paleolake-basin morphometry and structure should be kept in mind when planning an exploration program for sodium carbonate deposits. Some objectives should include locating the depocenter of the paleolake and determining the bulk mineralogy of drill core and outcrop samples in order to delineate possible zonation of authigenic minerals. The abundance of siliciclastic sediments including clay minerals should decrease, as carbonate sediments increase, basinward. The organic content of the carbonate muds may also increase basinward; Fischer assays, organic carbon analyses, or pyrolysis fluorescence analyses may be desirable to determine trends in organic content of the basinal sediments. Direct evidence of evaporites, such as crystal cavities and solution breccias, should not be overlooked. The densities of halite and sodium carbonate minerals (about 2) and that of the host sediments may contrast sufficiently to detect the evaporites by gravity surveys and by geophysical logs of exploration holes. Neutron logs should distinguish between hydrogen-bearing sodium carbonate minerals and halite.

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