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AN APPRAISAL OF THE NATURE AND SOURCE OF PORPHYRY COPPER DEPOSITS
Environments of Generation of Some Base-Metal Ore Deposits¹
A SUMMARY OF IDEAS ON THE ORIGIN OF NATIVE COPPER DEPOSITS
Crystallization Sequence of Minerals
Leading to Formation of Ore Deposits
in Quartz Monzonitic Rocks in the Northwestern
Part of the Boulder Batholith, Montana

Geological Society of America Bulletin, v. 73, p. 1257-1276, 3 figs., 1 pl., October 1962
1257
FLUID INCLUSION THERMOMETRY AND THE CARTERSVILLE MINING DISTRICT

To be presented at the Seventh Annual
Intermountain Minerals Conference; Vail, Colorado

July 1971

David L. Rife
Henderson Project
Climax Molybdenum Company
Empire, Colorado
When a heated mineral fluid cools to the point where crystal-
ization takes place, minute imperfections (cavities) occur in the
basic crystal structure. These cavities commonly trap, as primary
inclusions, very small amounts of the "mother fluid". When the
trapped liquid cools further, contraction causes the appearance of a
vapor bubble. By heating a mineral fragment containing liquid-vapor
inclusions to the point where the bubbles in the inclusions disappear,
we establish a minimum temperature at which the inclusions could have
formed from a heated mineral fluid at the time of entrapment.

This technique was applied to primary barite from the Cartersville
Mining District. Thermometric measurements on 250 primary liquid-
vapor inclusions in the barite resulted in a filling temperature range
of 126° - 297° C (uncorrected for pressure). Seventy-seven percent of
the temperatures cluster in a narrower range of 160° - 260° C. Since
all inclusions are more than half-filled with liquid and filling temper-
atures are well above those expected along a normal geothermal gradient,
a compatibility with hydrothermal derivation from a buried intrusive
is suggested. Mineralization probably occurred at depths ranging from
greater than 3000 feet to 5000 feet.

The Cartersville barite appears to be shallow, epithermal mineral-
ization formed from precipitation by very dilute barium-bearing solutions.
- Guidelines for Fluid Inclusion Studies -

I. Questions that can be answered by fluid inclusion work.

1. What temperature zoning can be determined?

2. Do variations in homogenization temperatures reveal different pulses of mineralization from a single source?

3. What chemical compositions and concentrations are to be expected in the fluids?

4. What was the extent of pre-existing burial?

5. Is the deposit a shallow emplacement or bonanza type?

6. Can a prediction be made of the particular depth a certain deposit may be expected to "bottom-out"?

II. Basic assumptions to be satisfied during fluid inclusion work.

1. The vacuole must have been completely filled with liquid at time of crystallization.

2. Morphology of inclusions is important because temperature values of secondary inclusions not related to the original mineral forming fluids may vary considerably within the same specimen.

3. Liquid within the inclusions must be an homogenous aqueous solution that does not contain carbon dioxide or another gas in large concentration.

4. The pressure exerted on the ore fluid at the time of emplacement was either small, or its magnitude can be estimated.

5. There must have been little significant change in the volume of the inclusion cavity due to pressure solution or precipitation.
6. There must have been no addition or loss of liquid from the cavity.

7. Representative samples must be used for temperature determinations.

III. Criteria for distinguishing type of inclusions.

1. Primary inclusions
   a) Occurrence in and along primary growth and color zones.
   b) Semifaceted
   c) Flat walls
   d) Free crystal faces
   e) Trough shaped
   f) Prominent ribbing along vacuole walls

2. Secondary inclusions
   a) Amoeboid (bird's-eye) shaped
   b) Dark in color - void of liquid
   c) Cross crystal growth boundaries without offset.
   d) Form networks of whispy trains of minute inclusions along fractures and healed cleavages.
Annotated List of some General References on Fluid Inclusion Work

Bailey, S. W., and Cameron, E. N., 1951, Temperatures of mineral formation in Bottom-Run Lead-Zinc deposits of the Upper Mississippi Valley, as indicated by liquid inclusions: Econ. Geol., v. 46, no. 6, p. 626-651.

Good reference on subject, authors spell out basic assumptions to be satisfied for fluid inclusion work.


Good paper on applied inclusion work; describes deposits, procedure, results, homogenization temperatures, sources of error, and concludes with an excellent discussion and summary.


Fundamental work on data for effect of concentration, curves for relations between homogenization temperature, pressure at time of formation, and temperature of formation.


Comparable paper describing P-v-T relationships with curves, and possible material migration along lineages and through crystals.


Good information on generalities of fluid inclusions in relation to ore fluid.

Roedder is the U.S. expert on fluid inclusion work and has published extensively on this subject.
Annotated List - continued


Probably the best all-around summary published on the subject; written for the layman and technician.


Fairly complete discussion of the general subject and written on a textbook level.


Negates most leakage on the basis of laboratory work and literature review.


Describes these deposits in light of fluid inclusion data with some good information on pressure of formation and pressure corrections with varying saline concentrations.


Voluminous, but probably the best Russian work published in English to date.
FROM: DOUGLAS M. SMITH, JR.

TO: WJK

The attached memo and article deal with the possible relationships between porphyry Cu deposits and calderas and appear to shed new light on the topic.

cc: FTG

RECEIVED

SEP 30 1985

EXPLORATION DEPARTMENT
Attention should be brought to an excellent article written by Gary T. Jones in a recent Economic Geology entitled "The Goonumbla Porphyry Copper Deposits, New South Wales" (1985, v. 80, p. 511-613). This article discusses regional exploration which has resulted in the discovery of nine deposits, the three largest comprising a resource of 250+ million tons with a mean grade of 0.70% Cu and 0.28 g/metric ton (.008 oz/ton) Au.

Key features are as follows:

1) The deposits are vertical pipes of stockwork and disseminated bornite, chalcopyrite, and chalcocite associated with small quartz monzonite porphyry intrusions. These intrude trachyte to andesite volcanics associated with a collapse caldera. The sequence of events proposed by Jones has the deposits forming at the end stages (resurgence?) of the caldera cycle; a history, if correct, that refutes Sillitoe's (1980) idea that resurgence is not conducive to porphyry copper generation. (The magmatic-hydrothermal fluids should have supposedly already been expelled by ignimbrite eruption.)

2) The small quartz monzonite mineralizing intrusions are believed to be late stage differentiates of a more mafic monzonitic magma. This is an important point, for I believe it is the alkaline nature of these rocks that has contributed the gold. It has important exploration significance for New Mexico as the state is filled with monzonitic intrusions. An intrusion with a complex igneous history appears called for; the Sierra Blanca region springs to mind as containing many monzonitic intrusions with complex histories.

3) Alteration associated with these deposits is typically potassic (pervasive pink K-feldspar flooding with lesser secondary biotite). Highest values are associated with quartz vein stockworks. Sericitic alteration may or may not be present peripheral to the potassic alteration. Beyond the potassic alteration is a zone of propylitic alteration.

4) Gold values are essentially restricted to the zone of potassic alteration. Silver (0.03-0.07 oz/T) tends to follow the gold. There is a strong correlation between gold and copper content (nearly 1:1 % Cu to grams/metric ton Au).
5) There is a strong wall-rock control on the distribution of the ore zone. The potassic alteration and volume of mineralization are greater in permeable pyroclastic wall rocks than in "tighter" flows.

At today's catastrophic copper prices, I have reservations whether a porphyry deposit even with a substantial gold kicker could be profitable. However, there is no reason to assume that gold grades higher than those contained within the Goonumbla deposits can't be discovered elsewhere.

A good place to start would be the Cerrillos District which contains small porphyry copper prospects associated with a complex monzonitic intrusion. Quick perusal of Asarco files reveals that significant Au anomalies were intersected in several drill holes. Moreover, organic-rich clastic sedimentary rocks occur at the periphery of the district; these hold potential for disseminated Au deposits (as at Portrerillos, Chile). Detailed mapping and sampling are recommended.

Paul J. Bartos

References

Sillitoe, R.H., 1980, Cauldron subsidence as a possible inhibitor of porphyry copper formation: Mining Geology Special Issue, No. 8, p. 85-93.
Mesozoic ash-flow caldera fragments in southeastern Arizona and their relation to porphyry copper deposits

Peter W. Lipman
David A. Sawyer
U.S. Geological Survey, Denver, Colorado 80225
Xerox copies of two items of interest (Geological Survey Research 1978) are attached.

(1) The Shultz "Granite" of the Globe-Miami District consists of a three-phase quartz monzonite intrusive. All disseminated sulphide mineralization is in, or adjacent to, the youngest phase --- the most conspicuously porphyritic. A close relation between the development of porphyry textures and the introduction of copper-iron sulphides is implied --- "whatever the nature of the ore-forming process."

(2) Results of laboratory work on rocks from the Ray District conflict with both the ortho-magmatic and meteoric water models of porphyry copper genesis. A new model is proposed, which ".....explains the failure to discover petrologic and chemical distinctions between 'ore' and 'non-ore' plutons." Regional structure is given renewed emphasis in exploration.
sumed to be related, although they differ in some respects. Recent interpretations of the origins of the two vein groups suggest that they are not related (Thayer, Case, and Stotelmeyer, 1977). The Canyon Mountain Complex is about 160 km² in area; about 50 percent ultramafic and 30 to 35 percent gabbroic rocks form a continuous metamorphosed cumulate sequence. About 20 percent of the complex consists of basaltic dikes and plagiogranite that form a composite sheeted dike unit and cut the gabbro along through-going fractures. The entire complex probably is of Early Permian age.

Chalcopyrite-bearing pyritic quartz veins are localized in the southwestern part of the gabbro, mostly within 600 m of the contact with the sheeted dike unit. The veins are associated with basaltic dikes, albite granite, and albite-chlorite-epidote alteration along shear zones. Although small epidotic quartz veins and lenses are common with albite granite in the sheeted dike unit, few of them contain sulfides. Sampling by the U.S. Bureau of Mines has indicated about 45,000 tons of material that averages 0.30 to 0.35 percent copper in two deposits. The larger deposit is in a zone about 750 m long that was followed by several basaltic dikes from an offset in the gabbro contact against the sheeted dike unit. The copper veins contain only traces of gold and silver.

Gold occurs in pocket quartz-calcareous veins that cut carbonatized gabbro and serpentinite in the northwestern corner of the complex. Gold-bearing veins also occur in greenstone and argillite north of the contact, and in Mesozoic rocks 2.5 km west of it. Gold production, mostly from nearby placer deposits, has been about 26,000 kg, with about 400 kg of silver and some platinum. The veins contain no copper. A major difference in ages of the gold and copper veins is indicated by gold veins west of the complex that cut Triassic conglomerate, which contains many clasts of albite granite. The gold veins appear to be related to Upper Jurassic diorite to granitic plutons in the Blue Mountain region. Petrogenetic relationships between gabbro, basaltic dikes, and plagiogranite are not known (Thayer, Case, and Stotelmeyer, 1977).

The close association of copper veins with basaltic dikes in gabbro suggest that their origin may be similar to the massive cupreous pyritic ores of Cyprus. The Canyon Mountain dikes are interpreted as feeders for pillow lavas that have been eroded away. In Cyprus, deposition of massive sulfides resulted from reaction of seawater with volcanic emanations, and ore-grade mineralization was shallow. It is postulated that the copper veins in the Canyon Mountain may represent former channels for solutions that formed massive sulfide deposits at higher levels on the Permian seafloor.

Characteristics of a porphyry copper stock in the Globe-Miami district of Arizona

In the Globe-Miami district of Arizona, the porphyry copper deposits are temporally and spatially related to the Schultze Granite, a porphyritic quartz monzonite stock of Laramide age. Recent geologic mapping by S. C. Creasey within the stock has shown that it is composite. The early intrusive phase contains more biotite and is not so conspicuously porphyritic. The intermediate, or main, intrusive phase is lighter in color and contains less biotite and larger and more abundant K-feldspar phenocrysts. The youngest intrusive phases are porphyries. All of the disseminated sulfide mineralization in the district is in, or adjacent to, the porphyries. Although not abundant, breccia pipes are also in, or near, porphyries and mineralized ground. The implication is clear that whatever the nature of the ore-forming process, the formation of porphyries is related to it in some way.

In addition the entire stock is cut by quartz-sericite-magnetite-sulfide veins ranging in width from less than 2 mm to perhaps 3 m, and in length from about a meter to as much as 650 m. These veins occupy fractures and are more abundant near the porphyry copper deposits. Although K-Ar ages on sericite from the veins indicate they are about the same age as the porphyry copper deposits, the small amount of development work on the veins suggests that they were low in base and precious metals. The origin of these veins is not clear, but the possibility of circulating meteoric water comes to mind.

Another model of porphyry copper generation

The orthomagmatic and meteoric water models of porphyry copper genesis find no support and considerable conflict in the data produced during detailed field and petrologic studies of the stocks associated with the Ray, Ariz., porphyry copper deposit, one of the 10 top producers of copper in the country. The studies, which resulted in a new model of ore generation (Banks and Page, 1977) included detailed geologic mapping; thin section and polished thin section petrography; fluid-inclusion work; whole rock major and minor chemistry; electron and ion microprobe analyses of igneous and alteration minerals for Cu, S, Cl, H₂A, F, and major elements; and petrology of the magmatic sulfide minerals. Very little copper and sulfur occur in the
rocks; and the data are best explained if the copper and most of the sulfur, chlorine, and water in the magmas were used by the igneous minerals during crystallization of the magmas. The stocks, and by analogy any parental upper crustal magma, thus were themselves unlikely to produce an ore fluid. Furthermore, not only did the stocks contain little copper and sulfur to supply to an ore fluid of circulating meteoric water, but also copper was more likely added to rather than extracted from the rocks in the outer parts of a circulation cell. Incorporated into the new model is the petrologic confirmation that sulfur is essentially insoluble in siliceous silicate melts, and it is postulated that sulfide minerals accumulate in a zone of partial melting around, but not in, pockets of magma. Some of the magma is mobilized and intruded into the upper crust. The sulfides, however, remain in the zone of partial melting until local or regional cessation of melting allows excess metamorphic and late magmatic water to be present, which remobilizes and transports the sulfides to upper crustal sites. The new model explains the time-space relationship of ore and magma. It also explains the failure of considerable research to discover petrologic and chemical distinctions between “ore” and “non-ore” plutons. The model places renewed emphasis on regional structure in delineating favorable zones and localities for discovery of ore.

**Geology of the Cuprite mining district of Esmeralda County in Nevada**

Studies by R. P. Ashley show that the Cuprite mining district contains mineralization of two different types and ages. The younger is characterized by intense acid-sulfate alteration that has converted Cambrian siltstones and Tertiary tuffs, flows, and volcanic sedimentary rocks to silicified, opalized, and argillized rocks. Mineral production associated with this alteration includes only minor amounts of sulfur, silica, and clay. Potential for substantial discoveries of commercial sulfur and clay is low, for silica the potential is high, and for gold and mercury it is low to moderate. Alunitic rock exists, but its tonnage is too small and its mineralogy too unfavorable for exploitation by presently contemplated commercial processes.

The older mineralization at Cuprite consists of base-metal veins (mainly copper-lead) with minor precious metal values (mainly silver) in unaltered to locally hornfelsic Cambrian siltstones. This mineralization is probably Mesozoic in age, associated with a buried pluton. These veins have little economic potential, but minor potential exists for disseminated copper mineralization at depth.

**Molybdenum mineralization in the Battle Mountain mining district of Lander County, Nevada**

Numerous base and precious metal deposits in the Battle Mountain mining district are related to Upper Cretaceous and middle Tertiary granodiorites to quartz monzonites emplaced into thick sequences of Palaeozoic sedimentary rocks. Molybdenum mineralization occurs sporadically throughout the district, but is especially concentrated in an elongate stockwork system near Copper Basin that is being studied jointly by T. G. Theodore and J. N. Batchelder (USGS) and D. W. Blake and E. L. Kretschmer (Duval Corporation). This system is related to numerous small Tertiary (?) quartz monzonite intrusions. Near Copper Basin the emplacement of most intrusive rocks was controlled by two prominent fracture sets, one striking N. 70° W. and the other north-south. The molybdenite mineralization, including very minor chalcopyrite, is related mostly to the N. 70° W. set. In addition, other mineralized fractures striking approximately N. 45° W. and N. 45° E. acted as important conduits for mineralizing fluids. Many of the molybdenite-stockwork veins and their selvages reflect locally intense potassic alteration, and the veins typically contain potassium feldspar-biotite-calcite-molybdenite, and quartz-molybdenite-calcite-potassium feldspar±white mica assemblages. The molybdenite-bearing veins contain abundant liquid plus vapor fluid inclusions. Preliminary fluid-inclusion studies of these veins suggest the bulk of the molybdenite mineralization occurred during circulation of nonboiling to slightly boiling, moderately saline fluids that range mostly between 8 and 12 weight percent NaCl equivalent. Temperatures were approximately 300° to 400°C. The values of δ18O of the water calculated to be in equilibrium with hydrothermal quartz from molybdenite-bearing veins are +5.7 to +6.2, an unusually restricted range suggesting significant isotopic exchange with the wallrocks. Last, the molybdenite-stockwork system has been intruded extensively by a series of late north-south-striking, westward-dipping quartz latite porphyry dikes associated with minor lead and zinc mineralization.

**West-northwesterly structural zone controlled gold mineralization at Manhattan in Nevada**

Geologic mapping by D. R. Shawe in the vicinity of Manhattan shows a major west-northwest-trending zone of faults that was probably a primary con-
The accompanying article (Att. A) by Coney and Reynolds is excellent and should be read by all. It provides abundant food for thought which you may care to digest slowly over the course of the summer during philosophical moods experienced while perched on lofty outcrops. For instance, we all know (don’t we?) that igneous provinces vary compositionally across the leading edge of a continental plate which is subducting or has subducted an ocean plate. This is due to compositional variations between magmas generated at different depths (and thus at distinct horizontal distances from the trench) within the Benioff zone (Dickenson, 1968; Dewey and Bird, 1970; Bateman and Dodge, 1970; Gilluly, 1973). We are also aware that metallogenic provinces display close relationships to petrologic provinces (Sillitoe, 1972 A & B; Sawkins, 1972; Smith, 1973). It follows then that the array of hydrothermal ore deposits associated with igneous activity in the greater southwestern U.S.A. should show a time and type distribution consistent with the S-shaped field shown on Figure 2 of the Coney-Reynolds paper. Evidence to the contrary is presented on Attachment B where a plot of radiometric ages of major Pb-Zn-Cu-Mo-Ag-Au deposits shows that mineralization did not follow inboard-outboard swings of igneous activity. Instead, these ore deposits concentrated in a zone 300 km ($L_W$) to 770 km ($L_E$) east of the trench up until mid-Cenozoic time when the inboard boundary began to push eastward, eventually reaching a distance from the trench of almost 1500 km. The timing of this inboard extension coincides nicely with the presence of a gently dipping imbricate subduction system believed to have been active under the western U.S. during middle Cenozoic time (Lipman, et al., 1971 & 1972). Since the limits of hydrothermal ore deposition remained rigid with time while those of volcanism and intrusion migrated, there must be more to magmas with ore potential than meets the eye. Dip angles of the Benioff zone during ore deposition are defined on Att. B by $L_W$ and $L_E$ as 20° to 12°, thus simple depth of magma generation is not the regulating factor. Perhaps distance traveled down the Benioff zone and therefore time spent by the ingredients within the zone is the key. Any ideas?

D.M. Smith, Jr.
DMS: slr
cc: WL Kurtz
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Cordilleran Benioff zones

Peter J. Coney & Stephen J. Reynolds
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PRESSURE GRADIENTS AND BOILING AS MECHANISMS FOR
LOCALIZING ORE IN PORPHYRY SYSTEMS

By CHARLES G. CUNNINGHAM, Denver, Colo.