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Distribution of Gold in Porphyry Copper Deposits

by Dennis P. Cox and Donald A. Singer

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Abstract

Analysis of 55 porphyry copper deposits demonstrates a continuum between porphyry copper-gold deposits emplaced at a median depth of 1 km, with a median size of 160 million tonnes of copper ore and a median content of 2.6 percent magnetite in the potassic alteration zone, and porphyry copper-molybdenum deposits emplaced at a median depth of 3.6 km with a median size of 500 million tonnes and little magnetite. Molybdenum commonly occurs in low-grade peripheral zones outside the copper ore body in the porphyry copper-gold type. Gold grades are less than .05 ppm in the porphyry copper-molybdenum deposits. Between these end-members is an economically important group containing significant amounts of both gold and molybdenum.

INTRODUCTION

This paper expands and refines ideas about the distribution of gold in porphyry copper deposits. Previous contributors in this area are Kesler (1973) who plotted gold, molybdenum, and copper content of porphyry ores on a triangular coordinate system and related gold and molybdenum content to tectonic environment; Sillitoe (1979, 1982) who noted the correlation between gold grade and magnetite content in the potassic alteration zones of porphyry copper deposits; and Sinclair and others (1982) who noted other factors such as deposit morphology that are correlated with gold content.

In this paper we review information on gold distribution within individual, well studied deposits and compare this to information from across a group of 55 deposits for which we have data on tonnage and on grade of copper, gold, and molybdenum (table 1). These data came partly from files of the U.S. Bureau of Mines (R. Rosencranz, written commun., 1983) and partly from other proprietary sources. Estimated premining tonnages, average grades, and the lowest available cutoff grades of well explored deposits were used. Because of the proprietary nature of some of these data, it is not possible for us to present them in a way that permits identification of individual deposit grades.

The deposits include 20 examples here classified as porphyry copper-gold deposits (PCD-Au) (typified by the Dos Pobres deposit in Arizona), 19 classified as porphyry copper-gold-molybdenum deposits (PCD-Au-Mo) (of which Bingham, Utah is a good example), and 16 classified as porphyry copper-molybdenum deposits (PCD-Mo) (typified by Sierrita-Esperanza, Arizona). The classification (following Kesler, 1973) is based on distribution of the deposits on a triangular coordinate plot showing their copper grade in percent, molybdenum content in percent times 10, and gold grade in parts per million (ppm) (fig 1). Our conclusions are that the three types differ significantly in metal content, magnetite content, deposit morphology, depth of emplacement, and tonnage.

FACTORS RELATED TO GOLD CONTENT OF PORPHYRY COPPER DEPOSITS

Copper-molybdenum content

In this paper we define the porphyry copper-gold model as having high gold and low molybdenum grade in a magnetite-rich potassic alteration zone of a porphyry copper deposit. Excluded are gold-rich copper skarn ore bodies, and porphyry systems where gold mineralization was clearly epithermal, younger, or distally related to the intrusion. Because of the gradational variation of gold content and its interdependence with molybdenum, it is not possible to define PCD-Au systems on the basis of gold content alone. Most of

the deposits contain 0.3 to 0.7 ppm Au but some deposits containing less than 0.2 ppm fit the model in other ways such as mineralogy and alteration zoning. The PCD-Au model can be defined more precisely in terms of gold and molybdenum grades according to the relation:

$$(1) \quad \frac{\text{Au}}{\text{Mo}} > 30$$

where Au is in ppm and Mo is in percent. Equation 1 is plotted on the triangular coordinate plot in figure 1 and separates a group of 20 deposits on the right-hand side that are all good examples of the PCD-Au model.

Gold occurs in porphyry copper deposits in various forms: micron size particles of free gold were described at Ingerbelle, B.C. (McCue, 1980); free gold is associated mainly with bornite, partly with chalcopyrite and negligibly with pyrite at Panguna, Papua New Guinea (Baldwin and others, 1978); small grains of electrum containing 11.5 to 18.5 percent silver are associated with bornite-gangue grain boundaries at Granisle, B.C. and with chalcopyrite and pyrite at Bell, B.C. (Carson and others, 1970; Cuddy and Kesler, 1982); and inclusions of sylvanite and hessite occur in bornite at Dos Pobres, Arizona (Langton and Williams, 1982).

Gold content is positively correlated with copper grade within some deposits such as Ingerbelle, B.C. (McCue, 1980) and Sapo Alegre, Puerto Rico (Cox and others, 1975). Cuddy and Kesler (1982) found a high correlation of gold grade with bornite content at Granisle, B.C. In some deposits such as Tanama, Puerto Rico (Cox, 1986), gold and copper grades are independent. For the 55 deposits used in this study, gold and copper average grades are independent at the one percent level of significance. Median copper grade for the data set is 0.48 percent Cu.

Within many porphyry deposits gold grade is negatively correlated with molybdenum grade as pointed out by Popov (1977) and Sillitoe (1982). The low molybdenum content of porphyry copper-gold deposits is related to the fact that, in many systems, molybdenum is distributed as a peripheral zone outside the copper-gold orebody that itself has a low molybdenum grade. At Dos Pobres (Langton and Williams, 1982), 0.005 to 0.015 percent molybdenum occurs in a quartz-sericite-pyrite alteration zone lying partly within the outer fringe of the > 0.5-percent -Cu orebody and partly outside of the orebody. A similar relation is cited by Sillitoe (1979) at Saindak, Pakistan; Bajo de Alumbrera, Argentina; and Dizon, Philippines.

This antipathetic relationship of gold and molybdenum, although not so well developed in other PCD-Au deposits, gives rise to an overall negative correlation of the two metals when data from all 55 deposits in the population are studied. The correlation coefficient between gold and molybdenum is low ($r=-0.45$), but is significant at the 1 percent level.

Of the 48 deposits for which a silver grade also was available, no correlation was found between silver content and that of gold, molybdenum, or copper (see figure 2). Median silver grade for the data set is 1.5 ppm.

Magnetite Content

Magnetite in veinlets makes up more than 1 percent by volume of most porphyry copper-gold ore bodies (Saegart and Lewis, 1977; Sillitoe, 1979). Magnetite forms stable assemblages with any of the minerals that characterize

potassic or feldspar-stable alteration: chalcopyrite, biotite, anhydrite, K-feldspar, chlorite, or actinolite. Excluded from this general rule are magnetite-rich skarn ore bodies and relict magnetite in replacement ore bodies in mafic igneous rocks such as at Ray, Arizona. The converse of this rule, that magnetite in porphyry copper ore bodies is positively correlated with gold content, has numerous exceptions. Magnetite is mentioned as a rare mineral at Poston Butte (Nason and others, 1982) and Sacaton (Cummings, 1982), Arizona. No gold grade is reported for these deposits. At Bethlehem, B.C., secondary magnetite appears as clusters with K-feldspar in the potassic alteration zone without attendant gold mineralization (J.A. Briskey, oral commun., 1984). At Mineral Park, Arizona (Wilkinson and others, 1982), a late magnetite-chalcopyrite-chlorite vein system cuts early quartz-K-feldspar-biotite-molybdenite veins. These veins form a low-grade copper zone (average 0.069 percent Cu) roughly coextensive with the molybdenum ore body containing >.03 percent Mo. According to Luis Vega (written commun., 1984), the Mineral Park porphyry system contains essentially no gold. Magnetite-chlorite veins are also associated with molybdenum mineralization in the Malala district of Sulawesi (Taylor and Van Leeuwen, 1980). Magnetite and molybdenite form fracture fillings in quartz porphyry. The Malala deposit contains 0.24 MoS₂ and subordinate amounts of copper.

Despite these exceptions, magnetite content is positively correlated with gold grade in the deposits included in this study. Where magnetite content is not given in percent in deposit descriptions, word descriptors were converted to numerical estimates according to the following scheme:

trace, rare	0.05
present	1
abundant	3

Magnetite content is plotted on the triangular diagram in Figure 3, and versus gold in Figure 4. The correlation coefficient ($r = 0.68$) is significant at the 1 percent level for 26 deposits for which an estimated magnetite content greater than zero was available (fig. 4). The deposit represented by the point with high gold and low magnetite content (upper left side of the field) had an original high content of magnetite that was largely replaced by pyrite during late stage phyllic alteration.

Deposit morphology

Sinclair and others (1982) applied the porphyry classification scheme of Sutherland Brown (1976) to a group of porphyry deposits in British Columbia and found that porphyry copper-gold deposits tend to be in classic and volcanic-type intrusive systems. According to Sutherland Brown, classic type deposits are centered around small cylindrical plutons. They are commonly associated with breccia pipes and have concentric zones of alteration and mineralization. Coeval volcanic rocks are commonly absent in these deposits. Volcanic-type deposits are related to irregular or dike-like igneous bodies that have intruded "a coeval and at least partly, consanguineous volcanic pile" (Sutherland Brown, 1976, p. 46). We have plotted on Figure 5 all deposits of volcanic type plus all those known to have coeval volcanic rocks exposed at or within a kilometer of the deposit. These deposits show a strong concentration on the PCD-Au side of the diagram. In contrast, plutonic-type porphyry deposits, characterized by mineralization in integral zones of medium-sized plutons with phanerocrystalline textures (Sutherland Brown, 1976, p. 48-49) are concentrated on the high-molybdenum, low-gold side of the diagram.

Depth of emplacement

Estimates of depth of emplacement, shown in Figure 6, were taken from geologic reports on individual deposits and from Sutherland Brown (1976, fig. 1). They show a negative correlation with gold grade of -0.90 , which is significant at the one percent level for 18 deposits (fig. 7). This correlation is expected, given the close relation between gold content and deposit classification because volcanic-type deposits tend to be emplaced at shallow levels in the crust and because the deep erosion required to expose plutonic-type deposits emplaced at deep levels in the crust commonly removes all traces of supracrustal volcanic rocks.

Deposit tonnage

Sillitoe (1979) noted no relation between deposit tonnage and gold grade in his set of 16 deposits having gold grade greater than or equal to 0.4 ppm. For our set of 55 deposits which includes a wider range of gold grades, there is a low correlation of -0.42 between deposit tonnage and gold grade, which is significant at the one percent level. Median tonnage of the PCD-Mo type is roughly three times that of PCD-Au type (table 2) and the tonnages are significantly different. Tonnage classes plotted on Figure 8 show a preponderance of small deposits on the gold-rich side and a concentration of large deposits on the high molybdenum side. This correlation is probably closely related to an inherent difference in tonnage between volcanic- and plutonic-type of deposits.

Associated igneous rocks

Descriptions of rock types believed to be genetically related to porphyry copper deposits were taken from the literature and converted into standard rock terminology (Streckeisen, 1973). These are plotted on figure 9. Of the 20 PCD-Au systems, 8 occur with tonalite or quartz diorite, 6 with syenite or monzonite, and 6 with granodiorite or monzogranite. Of the 16 PCD-Mo systems, 12 occur with monzogranite and granodiorite, 3 with tonalite, and one undetermined. Of 19 deposits classified as PCD-Au-Mo type, 13 were associated with monzogranite and granodiorite, 3 with tonalite, and 3 undetermined.

We agree with Sillitoe (1979) that associated rock type is not a good descriptor of porphyry copper-gold deposits. There is possibly a general tendency, not shown in the above data, for PCD-Au systems to be associated with the rocks rich in mafic minerals and for PCD-Mo and PCD-Au-Mo systems to occur with monzogranite and granodiorite having low mafic mineral content.

CHARACTERISTICS OF PORPHYRY COPPER-GOLD DEPOSITS

Porphyry copper-gold deposits have Au:Mo ratios satisfying equation 1 and median gold grades of 0.38 ppm (Table 2). The richest deposits contain 0.9 ppm (Sillitoe, 1979). Median molybdenum grades are $.003$ percent within copper-gold ore bodies but peripheral zones reaching $.01$ percent Mo may occur outside the copper-gold ore body. Median deposit tonnage is 160 million tonnes. The largest deposit, Panguna, Papua New Guinea exceeds one billion tonnes.

Porphyry copper-gold deposits tend to form in and around dike swarms or cylindrical plutons of tonalite or syenite-monzonite intruding coeval volcanic rocks (fig. 10). The ore-related intrusions may also be of granodiorite and monzogranite composition. In deposits for which depths of emplacement have

been estimated, the median depth is about 1 km. All deposits that have not been affected by pervasive late-stage phyllic alteration and pyritization have magnetite as a stable member of the potassic alteration assemblage. The median magnetite content is 2.6 percent.

CHARACTERISTICS OF PORPHYRY COPPER-GOLD-MOLYBDENUM DEPOSITS

Deposits in the PCD-Au-Mo class have, gold, and molybdenum contents that satisfy the relation:

$$(2) \quad 3 > \frac{\text{Au}}{\text{Mo}} < 30$$

where Mo and Au are each measured as in equation 1. Median gold grade for this class is 0.15 ppm and median molybdenum content is .015 percent Mo. Median tonnage is 390 million metric tons (Table 2). This class includes some large-tonnage deposits that, with their correspondingly high production rate, are important gold producers. Bingham, the largest deposit in this class, was for many years the second-ranking gold producer in the U.S.

Both classic- and volcanic-types of deposits contain gold together with molybdenum in copper ore bodies. In the classic type, gold is contained in both the intrusive porphyry and in related gold-rich skarn deposits such as at Bingham, Utah; Ruth, Nevada; and Santa Rita, New Mexico (fig. 11). Most deposits are related to intrusions of monzogranite and granodiorite composition. Magnetite is commonly present in the potassic alteration assemblage and the median magnetite content for 9 of these deposits is 1 percent. PCD-Au-Mo systems may have important additional gold mineralization in peripheral vein or replacement type deposits (fig. 11).

CHARACTERISTICS OF PORPHYRY COPPER-MOLYBDENUM DEPOSITS

Deposits of the PCD-Mo class have gold and molybdenum content defined by the relation:

$$(3) \quad \frac{\text{Au}}{\text{Mo}} \leq 3$$

where Mo and Au are measured in equation 1. Median molybdenum grade for this class of deposits is not significantly different from that of the PCD-Au-Mo class. Median gold values are .012 ppm. Median deposit tonnage is 500 million tonnes.

Classic-type porphyry copper deposits dominate the PCD-Mo class among U.S. deposits and plutonic-type porphyry deposits are important in British Columbia. Figure 12 is a cartoon showing characteristics of the latter type. Median depth of emplacement is 3.6 km (Table 2). Intrusions associated with ore deposition are mainly monzogranite in the U.S. and granodiorite or tonalite in British Columbia. Median magnetite content of potassic alteration zones is 0.05 percent. Some deposits have important gold-bearing vein, carbonate replacement, or skarn deposits arranged peripherally around the porphyry intrusion (fig. 12).

GEOCHEMICAL INTERPRETATION

Data presented by Chaffee (1982) show that, at San Manuel, Arizona, gold is concentrated in two environments, one within the porphyry copper ore body and the other about 1200 meters outward from the ore body in the propylitic alteration zone. This implies that two transport-deposition processes may be necessary to explain gold distribution in porphyry systems. One possible suggestion is that gold is deposited from gold complexes at high temperature

in the interior of the system, and that it is partly remobilized at lower temperature and relatively higher f_{S_2} conditions as thiocomplex ions and is transported to peripheral parts of the system. As Sillitoe (1982) has pointed out, high f_{O_2}/f_{S_2} ratios as evidenced by high magnetite to pyrite ratios in PCD-Au systems seem, in most cases, to be responsible for trapping gold in the copper-rich part of the system. Where the magnetite/pyrite ratio is low in the potassic alteration stage, sufficient sulfide ion may have been present to cause gold to remain mobile during falling temperature as gold thiocomplex ions (Henley, 1973). In such chemical environments gold would migrate outward to form peripheral gold vein-type deposits. One possible mechanism for maintaining high f_{O_2}/f_{S_2} ratios during the early gold-deposition stage might be the dissociation of H_2O to H_2 and O_2 . This reaction would be favored by the high temperatures and low pressures that would be associated with tonalite and other more mafic intrusions emplaced at high levels in the crust. Escape of the smaller hydrogen molecules would result in the high f_{O_2}/f_{S_2} ratio required to form magnetite and restrict gold mobilization.

The reason for molybdenum dispersal under high f_{O_2}/f_{S_2} conditions is not understood. Molybdenum is deposited where sulfide ion is concentrated both within copper ore bodies in PCD-Mo systems and within the peripheral pyrite zones around PCD-Au systems.

In this paper we recognize an economically important intermediate class of gold- and molybdenum-rich copper deposits in which neither the gold dispersal nor the molybdenum dispersal process has worked efficiently.

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Table 1. Porphyry copper deposits used in this study classified by their gold and molybdenum content.

Porphyry copper deposits		
<u>PCD-Au</u>	<u>PCD-Au-Mo</u>	<u>PCD-Mo</u>
Afton, B.C.	Ajo, AZ	Berg, B.C.
Basay, Philippines	Andacolla, Chile	Bethlehem, B.C.
Bell, B.C.	Bingham, UT	Brenda, B.C.
Caribou Bell, B.C.	Brenmac-Sultan, WA	Gambier Island, B.C.
Copper Mountain, B.C.	Cash, Yukon	Gaspe, Quebec
Dos Pobres, AZ	Casino, Yukon	Gibraltar, B.C.
Fish Lake, B.C.	Cerro Colorado, Panama	Highmont, B.C.
Frieda River, PNG	Copper Flat, N.M.	Huckleberry, B.C.
Galore Creek, B.C.	Dexing, China	Inspiration, AZ
Ingerbelle, B.C.	Granisle, B.C.	Lornex, B.C.
Mamut, Malaysia	Island Copper, B.C.	Morenci, AZ
Marcopper, Philippines	Kalamazoo, AZ	Ray, AZ
Ok Tedi, PNG	Morrison, B.C.	Sierrita-Esperanza, AZ
Panguna, PNG	Poison Mountain, B.C.	Tyrone, NM
Red Chris, B.C.	Ruth, NV	Twin Buttes, AZ
Rio Vivi, Puerto Rico	Schaft Creek, B.C.	Valley Copper, B.C.
Saindak South, Pakistan	Sipalay, Philippines	
Star Mountain, PNG	Yandera, PNG	
Tanama, Puerto Rico	Santa Rita, AZ	
Taysan, Philippines		

Table 2. Median grades, tonnages, and depths by type of porphyry copper deposit.

	Porphyry Copper Au type	Porphyry Copper Au-Mo type	Porphyry Copper Mo type
Number of Deposits	20	19	16
Tonnes x10 ⁶	160	390	500
Copper %	0.55	0.48	0.41
Molybdenum %	0.003	0.015	0.016
Gold g/t	0.38	0.15	0.012
Silver g/t	1.69	1.63	1.22
Magnetite content %	2.6	1.0	0.05
Depth km	1.0	0.9	3.6

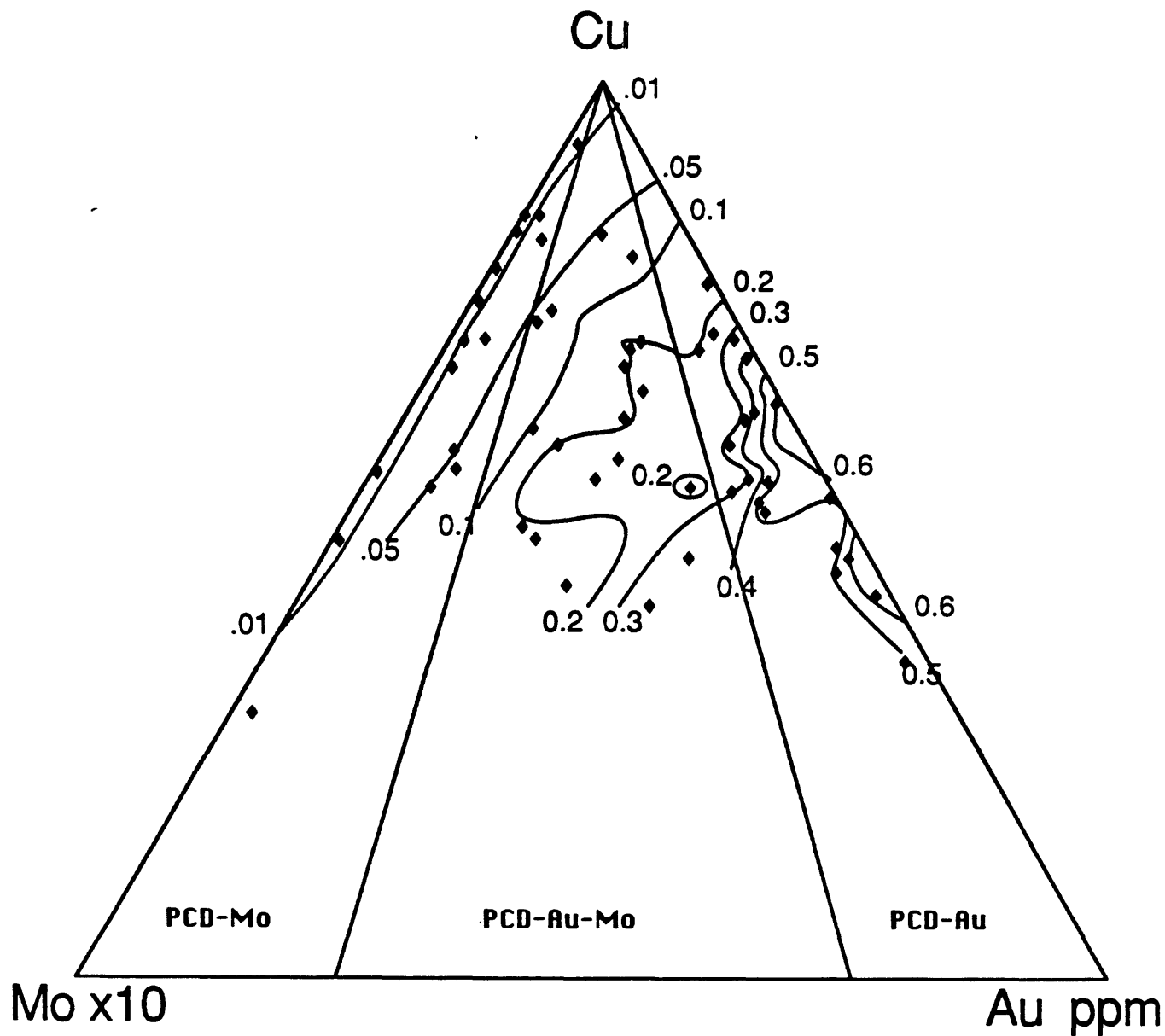


Figure 1. Fifty five porphyry copper deposits plotted according to their copper, gold and molybdenum content following Kesler (1973). Diamond symbols represent individual deposits. Contour lines represent gold content of deposits in grams per tonne. See text for explanation of subdivision into PCD-Au, PCD-Au-Mo, and PCD-Mo classes.

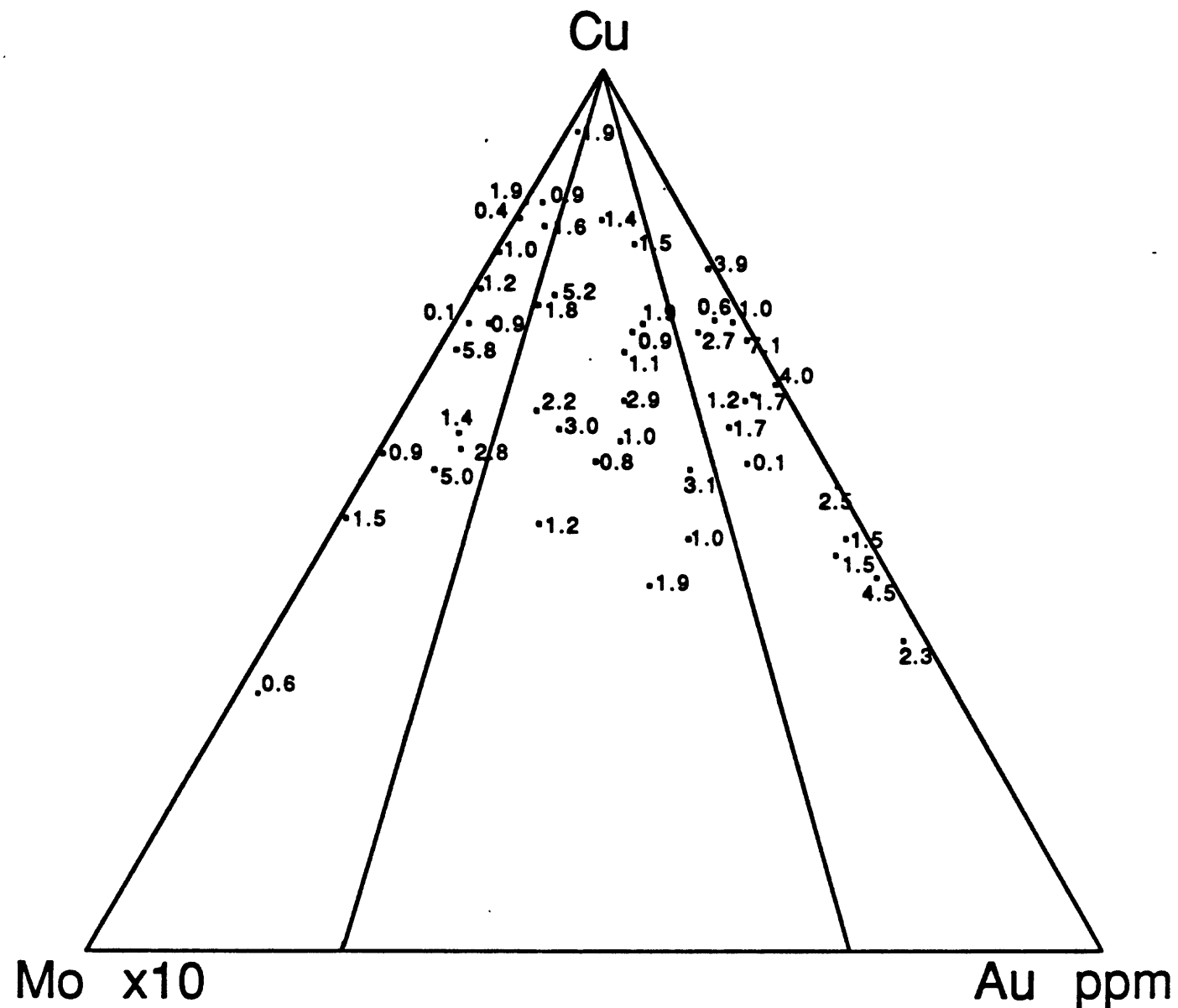


Figure 2. Triangular plot of silver grade of porphyry copper deposits in ppm. Positions of data points represent their copper, gold, and molybdenum content as shown in Figure 1. No systematic variation in observed.

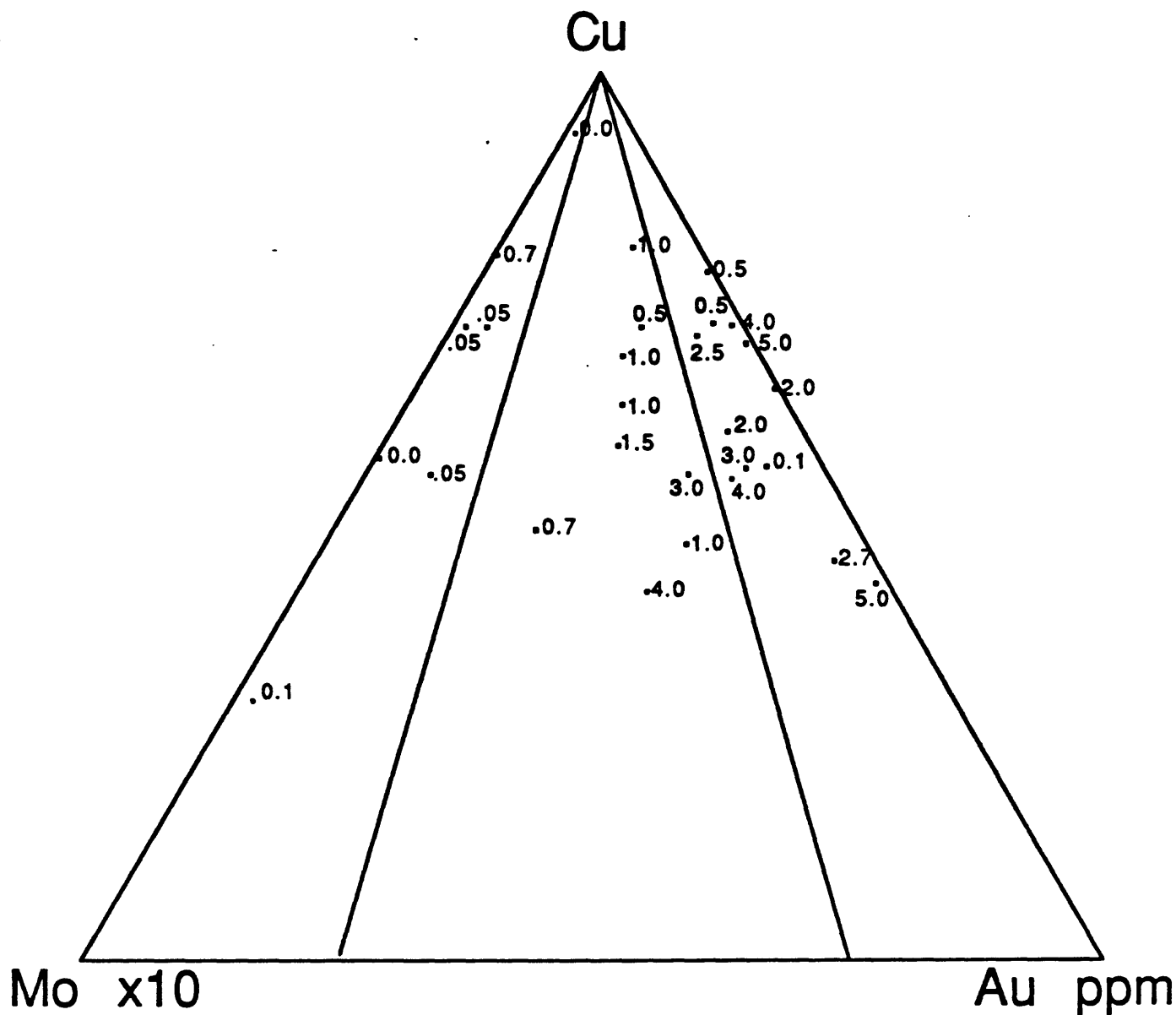


Figure 3. Triangular plot of magnetite content in weight percent in potassic alteration zones in porphyry copper deposits. Position of data points as in Figure 1.

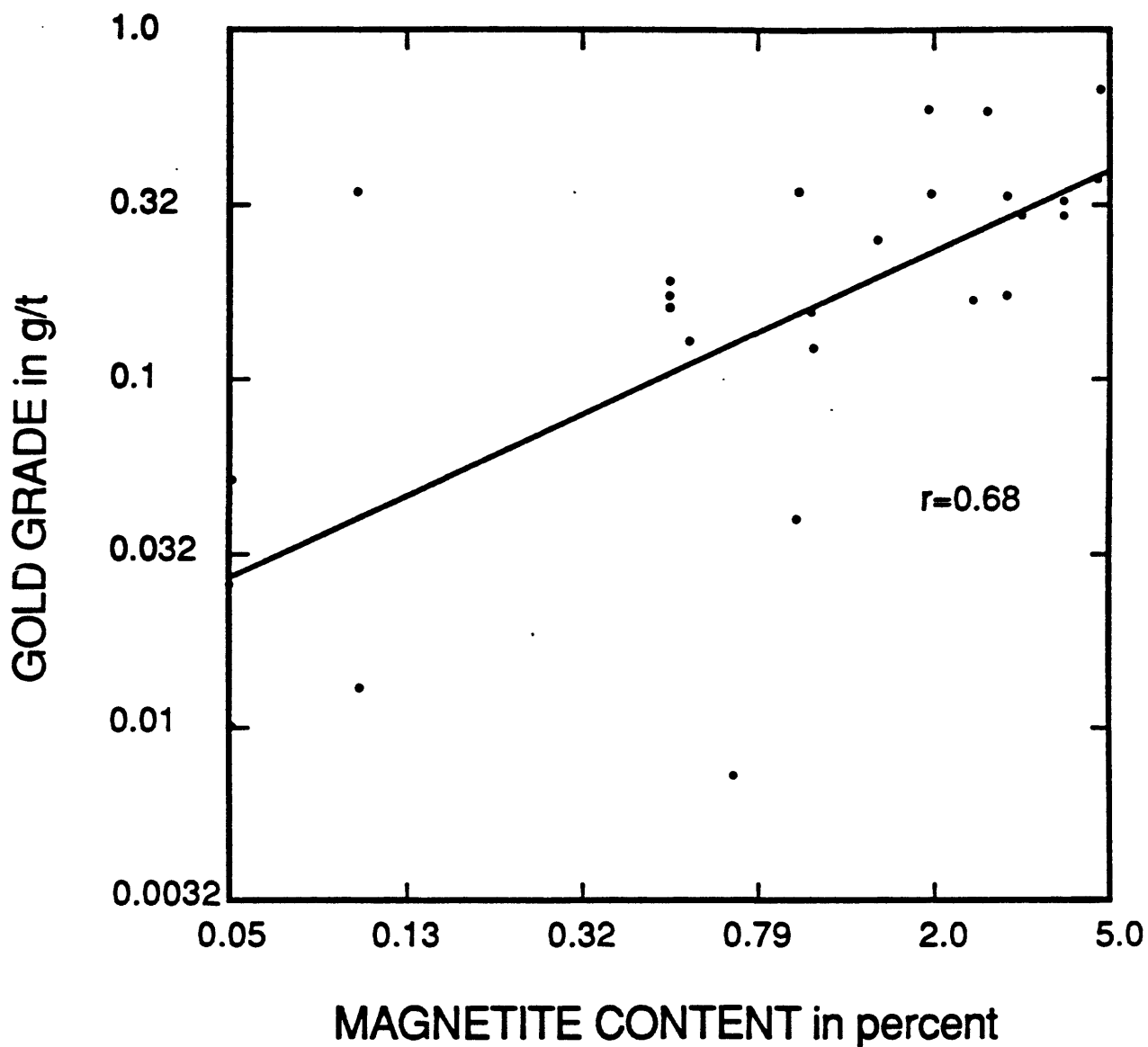


Figure 4. Plot of magnetite content vs. gold grade of 26 porphyry copper deposits. Correlation is 0.68 which is significant at the 1 percent level.

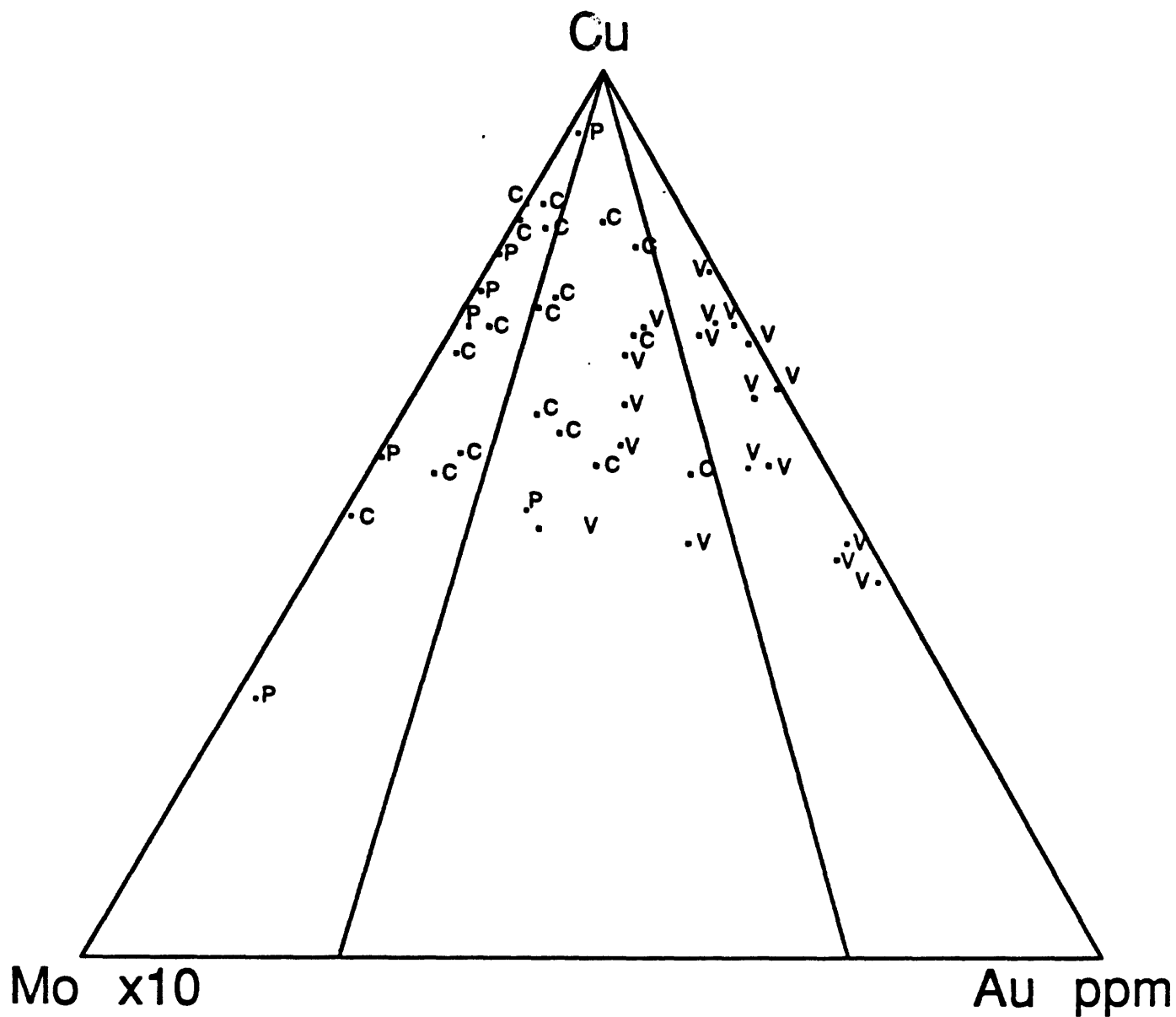


Figure 5. Triangular plot of porphyry copper deposits according to their morphologic class following Sutherland Brown (1976). V's represent volcanic-type plus some classic-type in which coeval volcanic rocks are abundant near the deposit. C is classic type and P is plutonic type.

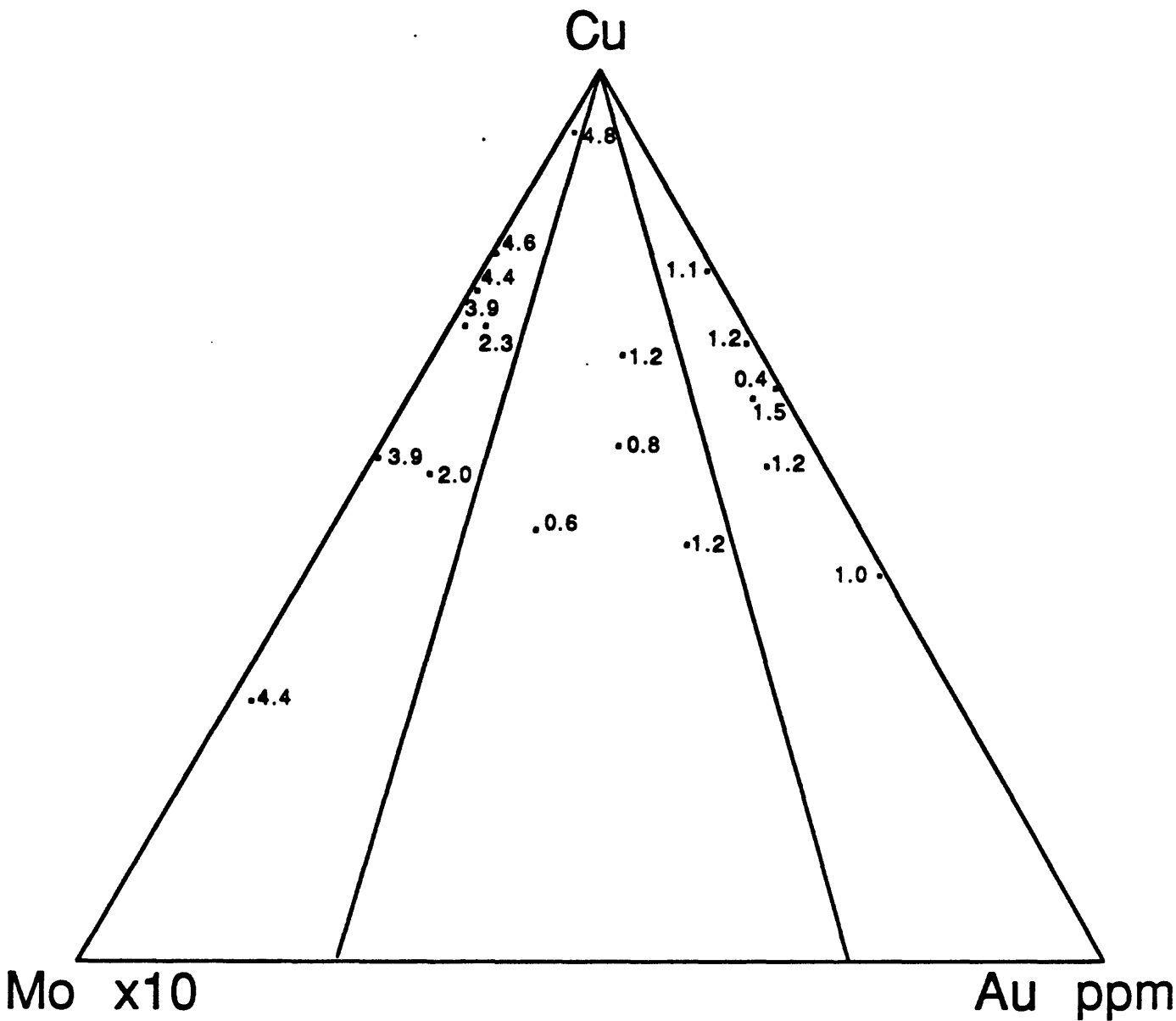


Figure 6. Triangular plot showing estimated depth of emplacement of porphyry copper deposits in kilometers.

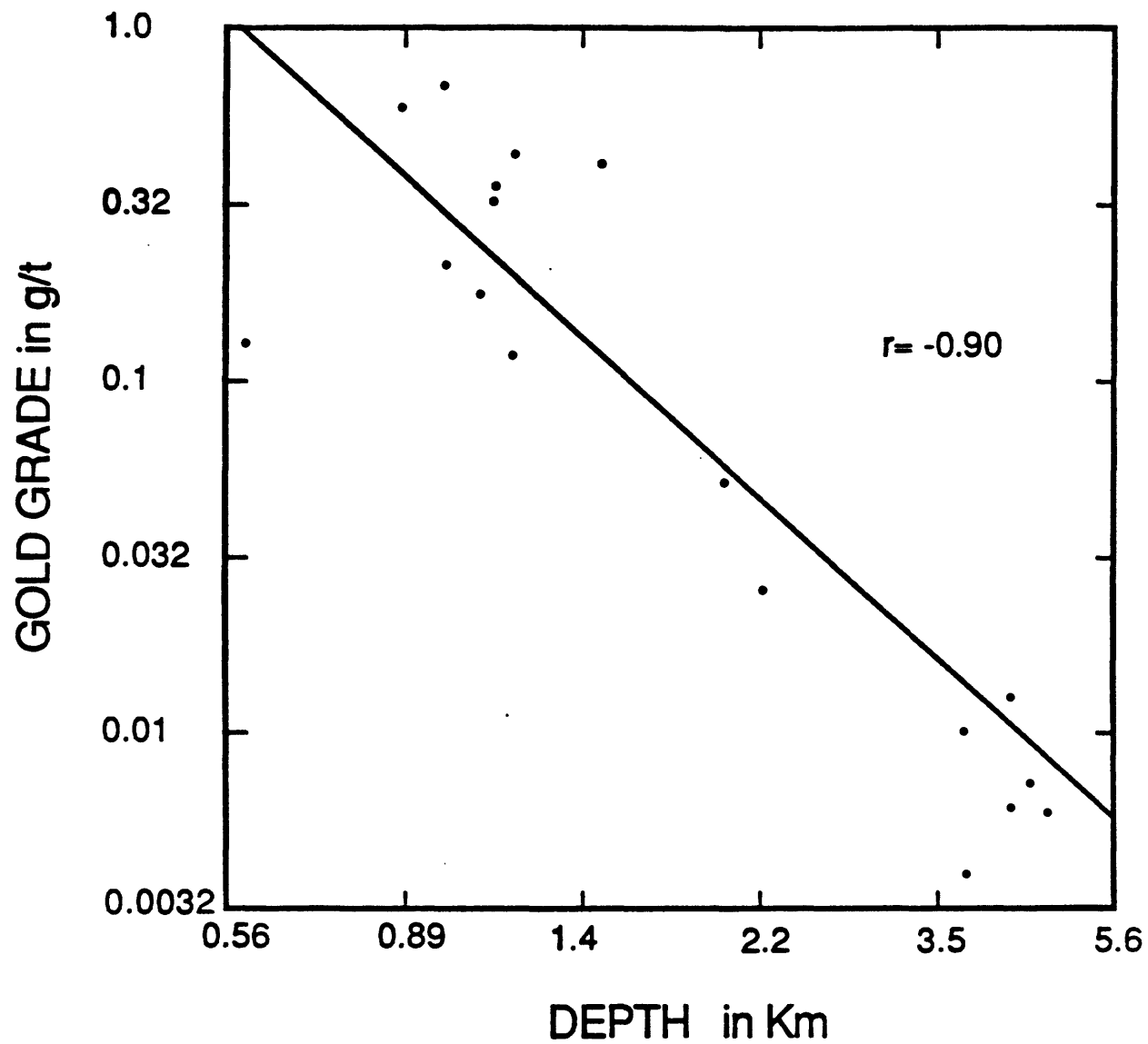


Figure 7. Plot of estimated depth of emplacement vs. gold grade for 18 porphyry copper deposits. The correlation is -0.90 which is significant at the 1 percent level.

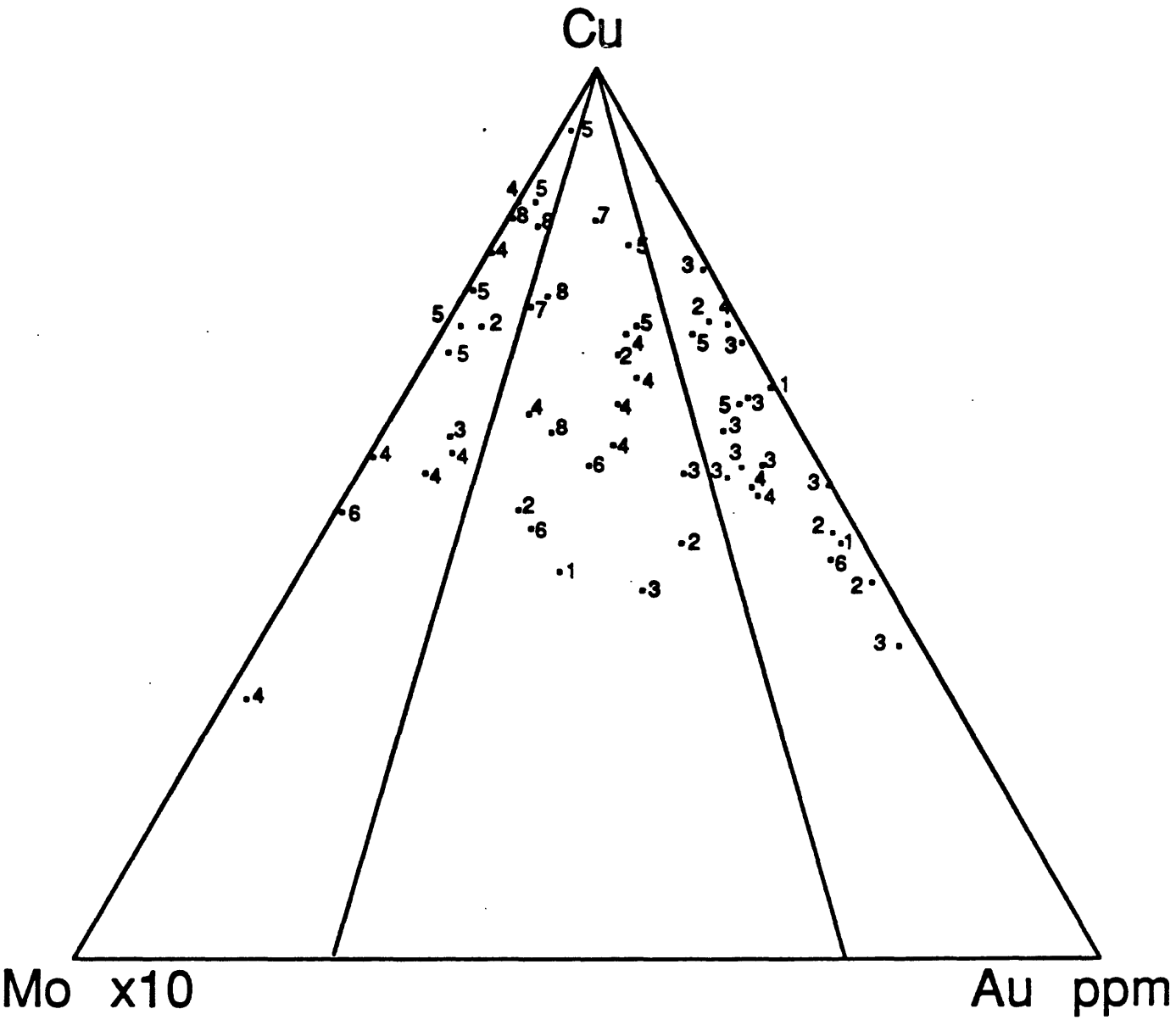


Figure 8. Triangular plot of tonnage classes, of porphyry copper deposits defined in millions of tonnes as follows:

- 1 = 0 to 50
- 2 = 51 to 100
- 3 = 101 to 200
- 4 = 201 to 400
- 5 = 401 to 800
- 6 = 801 to 1600
- 7 = 1601 to 3200
- 8 = 3201 to 6400

Correlation of gold content with tonnage is -0.42 which is significant at the one percent level.

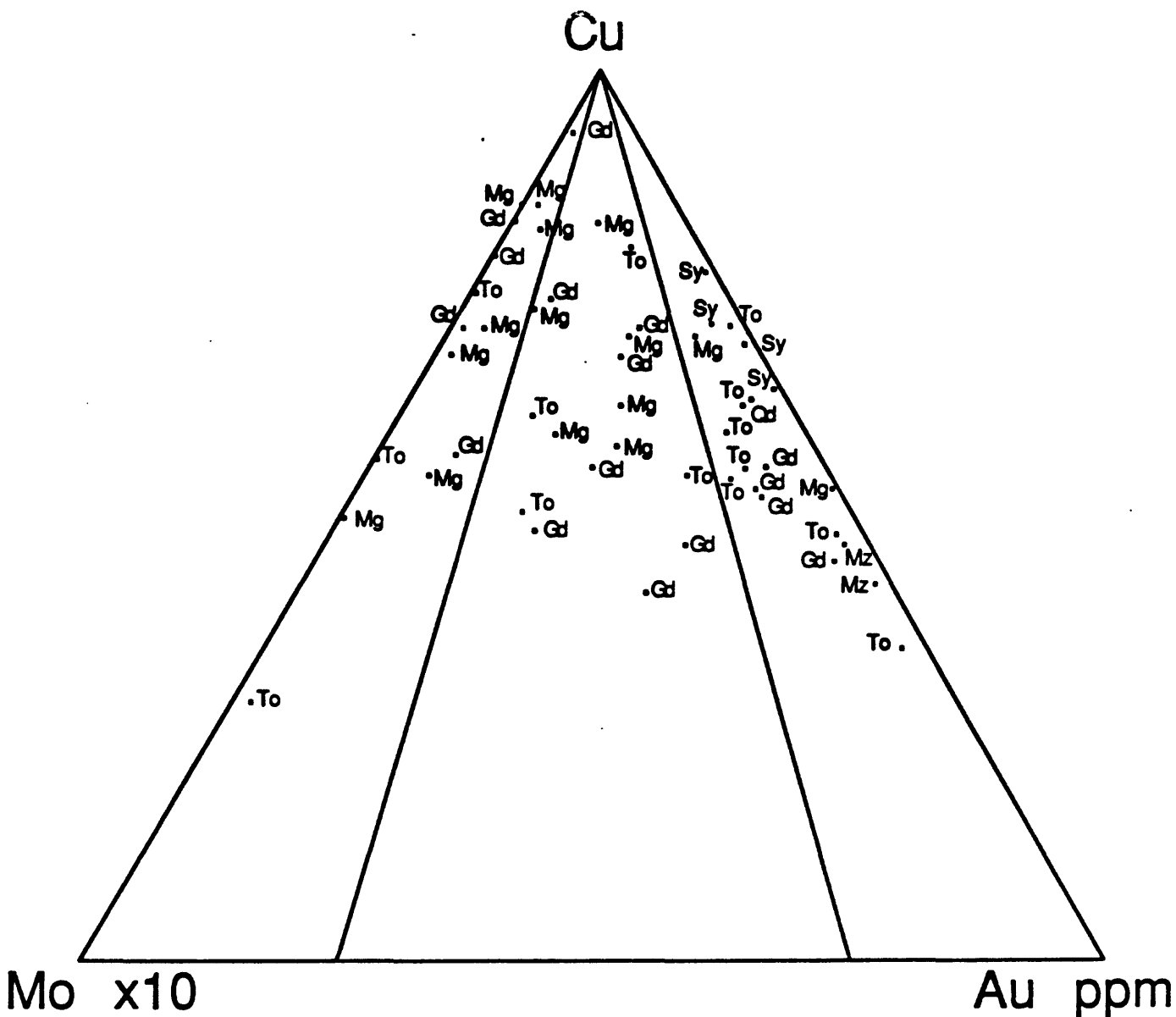


Figure 9. Triangular plot of type of ore-related intrusive rock in porphyry copper deposits: Mg, monzogranite; Gd, granodiorite; To, tonalite; Qd, quartz diorite, Mz, monzonite; Sy, syenite.

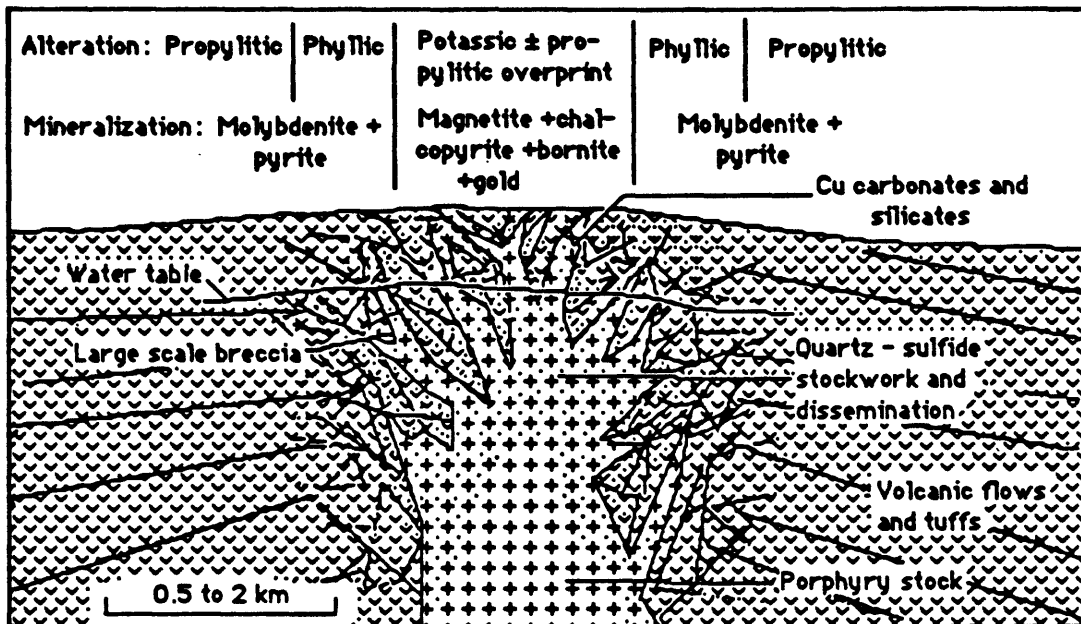


Figure 10. Cartoon cross section of porphyry copper-gold deposit as typified by the Dos Pobres deposit, Arizona. Modified from Langton and Williams (1982).

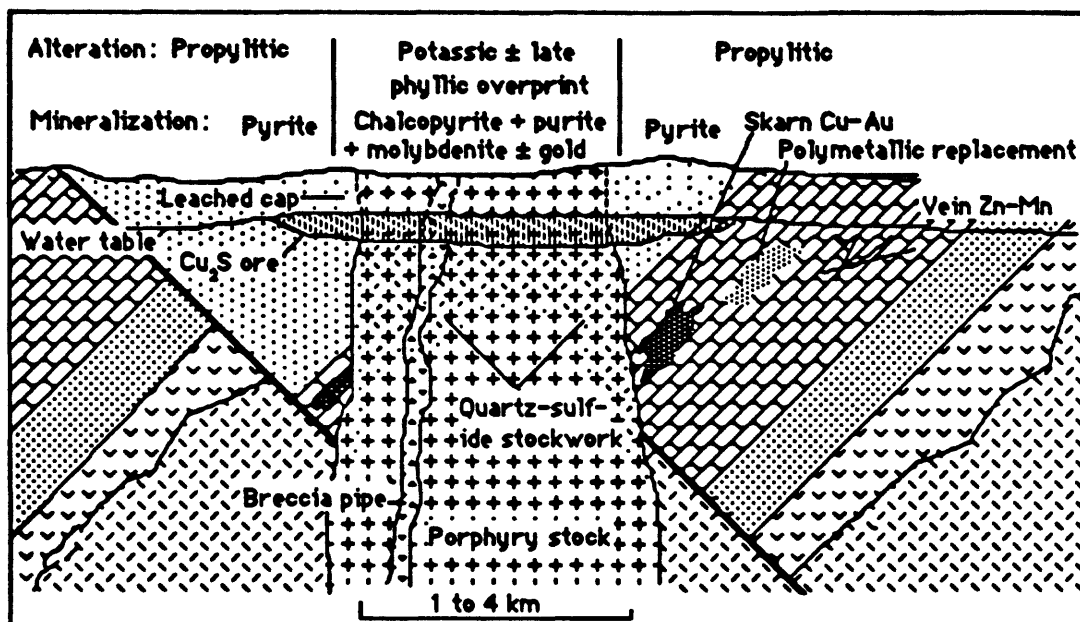


Figure 11. Cartoon showing cross section of a typical porphyry copper-gold-molybdenum deposit.

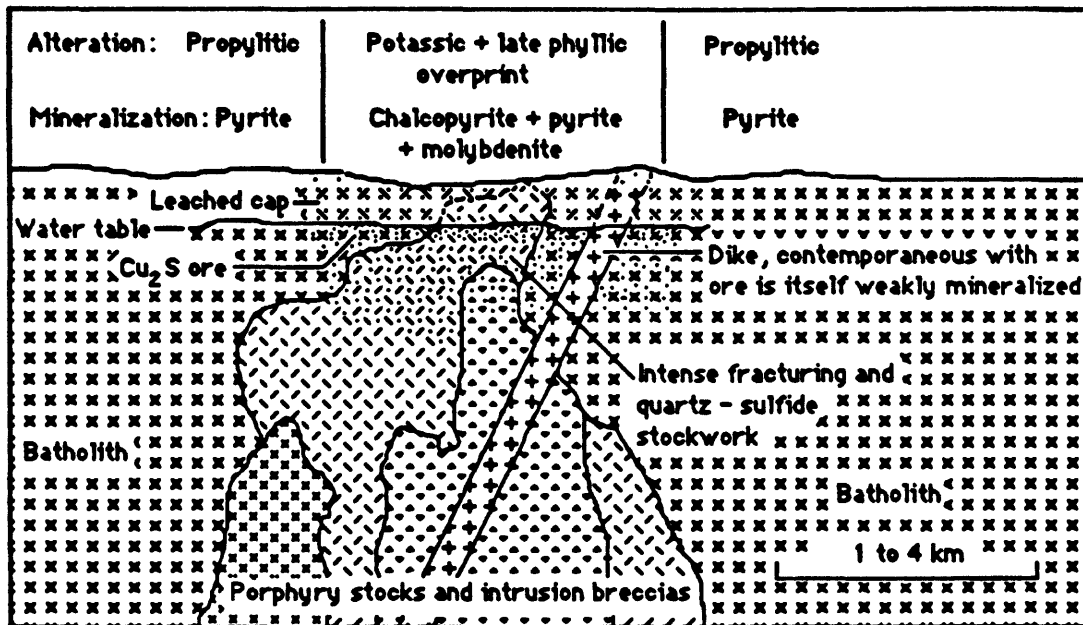


Figure 12. Cartoon cross-section of a typical porphyry copper-molybdenum deposit.