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GEOLOGICAL SURVEY

Gold in the United Verde massive sulfide deposit Jerome, Arizona

By

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INTRODUCTION

Location

The United Verde mine and the surrounding Verde mineralized district (Keith and others, 1983; Keith and others, 1984) are on the eastern slope of the Black Hills, near Jerome, Yavapai County, Arizona, about 140 km north of Phoenix and 64 km southwest of Flagstaff (fig. 1). Small massive sulfide deposits extend 9 km south-southeast from Jerome, but over 98 percent of the production from the Verde district has come from the United Verde and United Verde Extension mines at Jerome. Although other deposits will be referred to, only the massive sulfide deposit of the United Verde mine will be discussed in this report.

History

Prehistoric Indians and, later, Spaniards in the late 1590's discovered the deposits at Jerome and recovered some copper by surface mining, but the modern history did not begin until 1876-1877 with the location of claims that would later become the holdings of the United Verde Copper Company (Hamilton, 1884; Rickard, 1918). Senator W. A. Clark of Montana purchased the United Verde holdings in 1888 and operated the United Verde mine until 1935, when Phelps Dodge Corporation purchased the property. The deposit at the United Verde mine, which consists of the mined ore and lower grade ore remaining in the ground, is the largest known massive sulfide deposit in the United States and one of the largest in North America. The mine closed in 1953, but has since been leased to several parties conducting small-scale surface mining and leaching.

Production

Production records of the Phelps Dodge Corporation indicate that from 1889 until 1974 the United Verde mine produced nearly 33,000,000 tons of ore that yielded over 2,921,000,000 pounds of copper, 52,891,000 pounds of zinc, 49,279,000 ounces of silver, and 1,350,000 ounces of gold (table 1). Unpublished data from the Arizona Bureau of Geology and Mineral Technology indicate that from 1884 through 1888 and in 1975 an additional 27,000 tons of ore were produced that yielded about 6,900,000 pounds of copper, 324,000 ounces of silver, and 4,200 ounces of gold. Unpublished data from the same source indicates an additional 45,000,000 pounds of zinc and 459,000 pounds of lead were produced during the lifetime of the United Verde mine. From 1920 through 1940 the open pit operations produced 9,708,923 tons of ore that contained 674,734,000 pounds of copper, 20,529,100 ounces of silver, and 689,260 ounces of gold (Alenius, 1930, 1968; fig. 2A). From 1900 through 1975 the silver grade of ore decreased from over 4.0 oz per ton to 1.0 oz per ton (fig. 2B). During the same time gold grades decreased from approximately 0.085 oz per ton to 0.010 oz per ton, resulting in an increase of the Ag/Au ratio from 25 to 75 (fig. 2C). From 1884 through 1975 the ore averaged 1.49 oz per ton silver and 0.041 oz per ton gold, and had a Ag/Au ratio of 36.3. From 1903 through 1953 the gold grade of the ore had a crude positive correlation with copper content (fig. 3); the highest grade copper ores of 1903-1911 contained the highest gold values, and the lowest grade copper ores of 1940-1953 contained the lowest gold grades. This correlation is partly an artifact of the mining of oxidized ores with high gold content early in the history of the deposit. Gold grades from 1960 through 1975 did not follow the crude positive correlation with copper content, as much of the material mined during that time was from mineralized quartz porphyry and black schist (hydrothermally altered quartz porphyry), not from massive sulfide ore.

The Ag/Au ratio of the ore has varied over time and with the tonnage of ore produced (fig. 4). From 1901 through 1920, Ag/Au ratios increased with increasing underground production; as tonnage increased the gold grade decreased faster than the silver grade (figs. 2A, 2C). When open pit production began in 1920 and overtook underground production in 1922-1923, the Ag/Au ratio stabilized at 30 to 40 and was independent of tonnage produced through 1939 (fig. 4). From 1940 through 1944 the Ag/Au ratio increased to 50 to 70 and was inversely related to production; gold grades decreased faster than silver grades (figs. 2B, 2C). When zinc production began in 1944-1945, the Ag/Au ratio stablized at about 50 and was independent of tonnage produced. Notably, the gold grade increased slightly from 1945 through 1953 (fig. 2C), and zinc-rich ore contained as much gold as copper-rich ore (fig. 5).

Because only the copper-rich portion of the massive sulfide lens and surrounding rock was mined at the United Verde, a very large tonnage of low grade, probably subeconomic, ore remains in the ground. Reber (1922, 1938) estimated that only 14 to 20 percent of the original 90,000,000 ton ore body was of commercial grade (greater than 2 percent copper). Both Paul Handverger (written commun., 1974) and Paul Lindberg (written commun., 1977) estimated the deposit contained 80,000,000 to 100,000,000 tons of mineralized material, 75 percent of which remains in the ground. If the areas on figure 14 of Anderson and Creasey (1958) are used to calculate tonnages, approximately 115,000,000 tons of low-grade massive sulfide ore and 38,000,000 tons of mineralized black schist remain in the United Verde mine from the surface to the 4500 level. The grade of the massive sulfide material is unknown, but a conservative estimate, based on past production data, would be 0.5 to 1.0 percent copper, 2 to 4 percent zinc, traces of lead, 0.01 to 0.015 oz per ton gold, and 0.5 to 1.0 oz per ton silver. McIlroy and others (1974) indicate a resource estimate of 24,681,942 tons of ore that average 0.52 percent copper, 0.90 percent lead, 4.72 percent zinc, and 2.05 oz/ton silver, but give no values for gold grade. Using a cutoff grade of 4 percent zinc, Waegli and Jonathon Duhamel (unpub. data, 1981) estimate that the 500 through 3000 levels contain 20,857,000 tons of ore that average 0.52 percent copper, 6.6 percent zinc, 0.61 oz per ton silver, and 0.02 oz per ton gold.

Similar Deposits

The ore in the United Verde mine is interpreted to be a stratiform syngenetic deposit associated with submarine rhyolitic volcanism and hydrothermal alteration (Anderson and Nash, 1972). The orebody and associated volcanic rocks are very similar to Archean massive sulfide deposits of the Canadian shield (Hutchinson, 1973; Sangster, 1980; Franklin and others, 1981) and the Miocene Kuroko deposits of Japan (Ishihara, 1974). In the southwestern United States similar deposits of Proterozoic age are noted near Pecos, New Mexico (Krieger, 1932; Riesmeyer, 1978; Robertson and Moench, 1979), and in central and western Arizona (Anderson and Guilbert, 1979; Gilmour and Still, 1968; DeWitt, 1979; Baker and Clayton, 1968; Anderson, Scholz, and Strobell, 1955; Stensrud and More, 1980; and Donnelly and Hahn, 1981). In central and western Arizona similar volcanogenic massive sulfide deposits include the Iron King, Zonia, United Verde Extension, Old Dick-Bruce, Bluebell, Copper Chief, Desoto, and numerous smaller deposits.

GEOLOGY

Stratified Metavolcanic and Metasedimentary Rocks

The United Verde massive sulfide deposit lies at the top of a sequence of interbedded rhyolitic to basaltic volcanic rocks which have been metamorphosed to lower greenschist facies. Mixed sedimentary and volcaniclastic rocks overlie the massive sulfide deposit. Because original volcanic textures and structures are well preserved and deformation has not obliterated stratigraphic relations, the metamorphosed lithologies will be described by their protoliths. Detailed stratigraphy is described in Anderson and Creasey (1958) and Anderson and Nash (1972).

According to data in Anderson and Creasey (1958), volcanic rocks older than the massive sulfide deposit are a bimodal suite of basalt and basaltic andesite (40%) and rhyolite (55%), with only minor amounts (5%) of andesite and dacite (fig. 6). The mafic rocks include the Gaddes Basalt and Shea Basalt, both of which are pillowed lava flows with minor tuff and rhyolite breccia beds. The intermediate rocks are represented only by the Brindle Pup Andesite, a flow unit containing intercalated basalt and rhyolite flows. The felsic rocks include the Buzzard Rhyolite, dacite of Burnt Canyon, and Deception Rhyolite and allied minor intrusive rocks. These felsic extrusive units consist of flows, flow breccias, jasper-rich flows, and crystal and lithic tuffs. Porphyritic rhyolite (Cleopatra quartz porphyry) once thought to intrude the Deception rhyolite (Reber, 1922; Anderson and Creasey, 1958) is now included as an extrusive unit within the Deception (Anderson and Nash, 1972).

The chemical analyses in Anderson and Creasey (1958, tables 2, 4, 5, 6, 7, and 11), however, do not indicate such a bimodal suite. Their major element data are plotted on a classification grid (fig. 7; De la Roche and others, 1980) where the rock units are classified by their major element chemistry, not by their published name. Only samples that contain less than 3 weight percent water, less than 1.0 percent carbon dioxide, or are not described as being altered are used on figure 7. Even though a unit may be called an andesite (such as the Brindle Pup Andesite), its major element chemistry indicates the rock is a rhyodacite because of its position on figure 7. The one analysis of slightly altered Gaddes Basalt (not plotted on fig. 7) turns out to be a dacite, and the two analyses of Shea Basalt are actually andesite and dacite. The Buzzard Rhyolite and Deception Rhyolite (not plotted because altered) are truly rhyolites, and relatively unaltered Cleopatra quartz porphyry and unnamed quartz porphyries are rhyolite. Chemical data for the eleven fresh, unaltered volcanic rocks in the Jerome area, indicate that there is a complete range of compositions from andesite to rhyolite, and not a bimodal suite.

The pre-ore deposit volcanic rocks are predominantly calc-alkalic (Peacock, 1931), as shown by their combined Na_2O plus K_2O on figures 7 and 8A (Anderson, J. L., 1983). The Shea and Gaddes Basalts are low-K rocks (fig. 8B) and the rest of the units are either low- or medium-K rocks according to the classification of Peccerillo and Taylor (1976). The suite is predominantly metaluminous (Shand, 1927), but felsic rocks are slightly peraluminous. These rocks do not contain abnormally high concentrations of aluminum, but rather are slightly depleted in calcium, sodium, and potassium compared to metaluminous rocks with comparable silica. Most of the alkali depletion is related to hydrothermal alteration near ore bodies. Based on their Fe/Mg ratio (fig. 9), all the pre-ore deposit units are iron-rich (Miyashiro, 1974). The quartz porphyries and Cleopatra quartz porphyry exhibit a range from iron-rich to magnesium-rich behavior, but the magnesium enrichment is noted only in hydrothermally altered areas near ore bodies.

Metasedimentary and metavolcanic units that are syn- or post-massive sulfide deposit include coarse- and fine-grained tuffaceous rocks, volcanic breccia, chert and jasper beds, and dacite and andesite of the Grapevine Gulch

Formation. Chemically the dacite in the Grapevine Gulch is an alkali-calcic rhyolite, unlike older calc-alkalic units in the Jerome area (fig. 7). Crystal tuffs are locally abundant in the upper part of the Grapevine Gulch Formation, indicating that rhyolitic volcanism continued after deposition of tuffaceous rocks, minor limestone, and some agglomerate (Reber, 1922). Breccia beds in the basal Grapevine Gulch contain mineralized fragments of Deception rhyolite (Anderson and Nash, 1972).

The major element chemistry of unaltered volcanic units in the Jerome area is similar to that in the Prescott area to the west (fig. 7). Calc-alkalic basalt (tholeiite and olivine basalt) near Humboldt, Cleator, Townsend Butte, the Bluebell mine, and the Bell ranch, calc-alkalic to calcic dacite and rhyodacite in the Pine Flat and Battle Flat areas and west of Poland Junction, and calc-alkalic to calcic rhyolite and alkali rhyolite in the Indian Hills, Binghampton mine area, and near Cordes Junction are similar to the volcanic rocks near Jerome (fig. 1). Other rhyolites near Mayer and Mt. Elliott are alkali-calcic, and similar to rhyolite and rhyodacite in the Grapevine Gulch and Brindle Pup units, respectively. As at Jerome, volcanic units near Prescott are predominantly iron-rich, with only the dacite and rhyodacite near Pine Flat and Battle Flat and the rhyodacite west of Poland Junction being magnesium-rich (fig. 9). Prescott area basalts are low-K rocks, and intermediate to felsic units are low- or medium-K rocks; only the rhyolite bodies near Mayer and Mt. Elliott plot as high-K rocks (fig. 8B).

The pre- and post-ore deposit rocks have been described as having formed in a volcanic environment (Anderson and Creasey, 1958), in a greenstone belt (Anderson and Silver, 1976), and in volcanic arcs with distinct polarities and chemical evolution (Phillip Anderson, 1978). Vance and Condie (1986) suggest that the volcanic rocks formed in a combination of arc and back-arc settings.

Intrusive Rocks

All pre-ore metavolcanic and metasedimentary units have been intruded by minor quartz porphyry dikes, an extensive gabbro (United Verde Diorite of Reber, 1922), and later andesite(?) porphyry dikes. In the southern part of the Jerome area a 1740 ± 15 Ma (million-years-old) quartz diorite pluton (Anderson and Creasey, 1967; Anderson and others, 1971; date recalculated using decay constants in Steiger and Jaeger, 1977) intrudes those units. The gabbro in the United Verde mine area was intruded as a sill near the contact of the Grapevine Gulch Formation and Cleopatra Rhyolite, and locally cut out and isolated pieces of the massive sulfide deposit (Haynes orebody; plate 7 and figure 24 of Anderson and Creasey, 1958; Plate X of Reber, 1938; Anderson and Nash, 1972). The gabbro is not as foliated as the rocks it intrudes, but has been metamorphosed to the same degree as the stratified rocks. Chemically, the gabbro has been extensively altered (high H_2O, CO_2, Al_2O_3) and cannot be chemically named as other rock units are on figures 7, 8, and 9.

A swarm of east-trending, low-grade metamorphosed andesite(?) dikes intrudes the gabbro and massive sulfide lens in the United Verde mine (Provot, 1916; Reber, 1922). The dikes are undeformed but do contain sparse pyrite and chalcopyrite (Anderson and Creasey, 1958). Apparently the dikes were emplaced after regional deformation ceased, and the heat from the dikes caused very local remobilization of sulfide minerals.

Regional Structure and Age of Metamorphism and Deformation

The stratified volcanic sequence that underlies the massive sulfide deposit has a minimum age of 1,770 to 1,780 Ma, the U-Pb zircon date of the Cleopatra quartz porphyry member of the Deception Rhyolite (L. T. Silver, written commun., 1982). Regional deformation and low grade metamorphism of this 1,770-1,780 Ma sequence, along with the younger Grapevine Gulch Formation and gabbro, occurred between 1,770 Ma and 1,690 Ma, the K-Ar cooling date of the 1740 $\pm$ 15 Ma late-tectonic quartz diorite batholith south of Jerome (fig. 6). The syngenetic stratiform massive sulfide deposit in the United Verde mine is therefore dated at about 1,770 to 1,780 Ma.

Varied structural interpretations of the Jerome area have been proposed by Anderson and Creasey (1958), Anderson and Nash (1972), Lindberg and Jacobsen (1974), and Norman (1977) that involve from one to three major deformational events. The interpretation favored in this report incorporates much of Anderson and Nash's (1972) stratigraphy and follows Lindberg and Jacobsen's (1974) model for two generations of folding (figs. 6 and 10). In the area south of Jerome the northwest-trending Jerome anticline (F_1, fig. 6) has been cross folded about west-northwest-trending axes. The regional foliation in the metamorphosed lithologies parallels the second generation of folds (F_2, fig. 6). Locally, as near the United Verde mine, F_1 and F_2 structural features are parallel and the effects of refolding are not apparent.

ORE DEPOSITS

Structure

The United Verde massive sulfide body is localized near the top of the Cleopatra quartz porphyry member of the Deception rhyolite, and in the overlying Grapevine Gulch formation (fig. 10). The deposit and country rocks have been folded about north-northwest-trending axes, resulting in a pipe-shaped stratiform deposit that trends N20W and plunges 65 degrees to the north, parallel to minor folds and axial plane lineations (Anderson and Creasey, 1958). The plunge of the body increases with depth. Above the 1100 level the plunge averages 45 degrees; from the 1100 level to the 3300 level it averages 70 degrees; and from the 3300 level to the 4500 level it is vertical or reverses plunge to the southeast. A sill-like body of gabbro which isolates and cuts off portions of the top of the ore body (see pls. 7 and 10 of Anderson and Creasey, 1958) was emplaced along the Cleopatra quartz porphyry-Grapevine Gulch Formation contact.

The deposit is zoned from stratigraphic bottom (Cleopatra quartz porphyry member of the Deception Rhyolite) to top (Grapevine Gulch Formation) and consists of: 1) chloritized rhyolite or quartz porphyry; 2) copper-rich black schist, a hydrothermal alteration product containing massive chlorite derived from rhyolite; 3) copper-rich massive sulfide ore containing variable amounts of zinc; 4) copper-poor, zinc-rich massive sulfide ore that forms most of the deposit; 5) copper-zinc-poor, pyrite-rich massive sulfide ore; and 6) jaspery chert lenses (Reber, 1922; Anderson and Creasey, 1958). The black schist ranges from 0 to 60 m thick, the massive sulfide from 0 to 120 m thick, and the chert from 0 to 40 m thick. The massive sulfide body grades downward into black schist and ultimately rhyolite, but its upper contacts with chert, Grapevine Gulch rocks, or rhyolite are sharp and discrete. Laterally, the massive sulfide grades into and is interbedded with rhyolite and Grapevine Gulch lithologies.

The sulfide mass is exposed from the surface to the 4500 foot level of the mine, and undoubtedly once extended upward to the overlying Cambrian Tapeats Sandstone, an additional vertical distance of 120 m. The sulfide body therefore had a minimum length of 1600 m. The massive sulfide portion of the deposit varies in thickness from 12 to 18 m on the 4500 level to over 120 m on the 1650 level. It ranges in width from discontinuous zones 75 to 160 m wide on the lower levels of the mine to a continuously mineralized zone over 420 m wide on the 3000 level. The massive sulfide ore body is approximately pipe- or molar-shaped from the surface to the 1650 level, crescent-shaped from there to the 3300 level, and lens-shaped in the lowest parts of the mine (Anderson and Creasey, 1958, pl. 7). This variation in shape reflects both the original configuration of the deposit and the effects of folding.

Wallrock Alteration

Both the Cleopatra quartz porphyry and tuffaceous units of the Grapevine Gulch Formation below and adjacent to the massive sulfide lens have been variably chloritized and sericitized. Chloritization has created the black schist in the mine area and is probably the product of hydrothermal alteration of the rhyolite by seawater brine (Anderson and Nash, 1972). Sericitization of the rhyolite is more widespread than chloritization, but is not as pervasive and may not be totally related to the ore-forming process. Instead, some of the sericite may represent pre-metamorphic devitrification and alteration of glass and pumice within the rhyolitic units (Anderson and Creasey, 1958). Microprobe analyses indicate that chlorite in the black schist from the United Verde mine is ripidolite (classification of Hey, 1954) with a Fe/Fe+Mg ratio that ranges from 0.37 to 0.49 (Nash, 1973). The same chlorite would be classified as prochlorite by Saggerson and Turner (1982). The magnesium content of the ripidolite in the Cleopatra quartz porphyry increases, from south to north, with proximity to the United Verde mine. Similar magnesium-rich chlorite (Fe/Fe+Mg ratio of 0.31 to 0.56) has been reported from the alteration pipe of the Bruce massive sulfide deposit near Bagdad, Arizona (Larson, 1984).

Mineralogy

The original mineralogy of the United Verde deposit is simple and has been modifed only slightly by weathering or supergene processes. Ore minerals in the massive sulfide lens are, in decreasing order of abundance, pyrite, sphalerite, chalcopyrite, bornite, arsenopyrite, galena, tennantite, and gold (probably electrum). Gangue includes quartz, carbonate minerals, chlorite, sericite, and minor hematite. The same minerals, in about the same relative abundances, occur in the black schist ore and Cleopatra quartz porphyry ore, but chalcopyrite and bornite are more abundant than sphalerite in these ores. Chert that overlies the massive sulfide lens contains less pyrite and more chalcopyrite, sphalerite, hematite, and magnetite than the other ores. Naturally oxidized ores above the 160 level and ores oxidized by mine-fires down to the 600 level contained cuprite, chalcocite, azurite, malachite, native copper, wire silver, minor copper hydroxide minerals, limonite, and hydrous copper sulfate minerals (Reber, 1922; Lindgren, 1926; Anderson and Creasey, 1958).

Pyrite, sphalerite, and chalcopyrite in the massive sulfide lens and black schist are intergrown in a banded to massive texture that ranges in average grain size from 1 mm to less than 0.02 mm (Lindgren, 1926; Ralston, 1930; Slavin, 1930). Galena is normally finer grained than the other sulfide minerals and is interstitial to pyrite and sphalerite. The overlying chert and underlying black schist ores are slightly coarser, but very fine grained. This fine-grained and intergrown nature of the ore made high recoveries of both base and precious metals difficult (Barker, 1930).

Gold is apparently present as electrum in microscopic inclusions within most sulfide minerals, and the gold may contain significant silver. Unfortunately no studies have been made of the mineralogy or occurrence of gold and silver. Much silver is present in late-stage tennantite in quartz-carbonate veins and carbonate-rich massive sulfide ore (Anderson and Creasey, 1958, table 16). This tennantite also contains significant gold, most probably as microscopic inclusions.

Lead Isotope Data

Galena from the United Verde deposit was first analyzed for lead isotope ratios by Mauger, Damon, and Giletti (1965) who reported a 1767 Ma single-stage-model lead date (date recalculated using data in Appendix C, Doe and Stacey, 1974) for the apparently conformable base metal deposit. Subsequently, Stacey and others (1976) reported galena from the deposit to have the following lead isotopic ratios: $^{206}Pb/^{204}Pb = 15.725$; $^{207}Pb/^{204}Pb = 15.270$; $^{208}Pb/^{204}Pb = 35.344$. A single stage model lead date calculated for this galena, again using data in Doe and Stacey (1974), is 1729 Ma, but the point falls slightly off the single stage growth line on a $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ diagram. Stacey and others (1976) indicate that the galena analysis from the United Verde deposit falls in between their curves for lead from the mantle and lead from a well mixed orogene, and suggest that their two-stage-model isochron date (Stacey and Kramers, 1975) of 1645 Ma is a result of lead from the mantle being mixed with lead from an orogenic or marine source that was of a slightly more radiogenic nature than the mantle lead. The age discrepancy of about 130 m.y. between the preferred age of the host rocks (about 1775 Ma) and the two-stage galena date is a function of isotopic mixing in an orogenic setting.

Gold-Silver Zonation

As previously noted, the most obvious change in content of precious metals in the deposit is from unoxidized to oxidized ore, where gold and silver grades increase by almost an order of magnitude (Au, 0.03 oz per ton in unoxidized ore to 0.2 oz per ton or greater in oxidized ore; Ag, 1.2 oz per ton in unoxidized ore to 15.0 oz per ton or greater in oxidized ore). However, gold and silver contents also vary considerably within the unoxidized ore where their grades are related to the type of ore. Smith and Sirdevan (1921, table 3) were perhaps the first to show that silica-rich (converter) massive sulfide ore contained more gold and silver than normal massive sulfide (iron) or black schist (silica) ore. Subsequently, Hansen (1930), Barker (1930), and Ralston and Hunter (1930) enlarged upon these findings and indicated that the ore ranged from low precious-metal contents in quartz porphyry and black schist ore to high contents in massive sulfide and siliceous massive sulfide ore. Their data suggested that the deposit was zoned and that precious metal contents were greatest at the stratigraphic top.

This variation of gold and silver within ore types is further quantified by using the data of Storms (1955) for various levels within the United Verde deposit. Massive sulfide ore on the 700 level averages 10 times as much gold and 4-5 times as much silver as black schist ore on the same level (table 2). Massive sulfide ore on the 3000 level averages 3-4 times as much gold and 2 times as much silver as black schist ore on the same level. Gold and silver grades range from 0.002 oz per ton and 0.71 oz per ton, respectively, in black schist ore, to 0.116 oz per ton and 4.0 oz per ton in chert ore on the 4500 level. Clearly the content of precious metals is highest at the stratigraphic top of the deposit and gold is more enriched than silver near the top.

Correlations between precious and base metals in the deposit are not obvious if ore types are not differentiated (fig. 11A-F). Copper, zinc, gold, and silver analyses for a suite of samples on the 2400 level show no high positive or negative correlations among the four variables (fig. 11). An important feature to note from figure 11 is that the gold and silver grades, although not positively correlated with either copper or zinc content, are just as high in zinc-rich ore (fig. 11B, F) as in copper-rich ore (fig. 11C, D).

If the various ore types are separated and the data in Storms (1955) are plotted, correlations are noted (fig. 12, table 3). The Ag/Au ratio and precious metal grades vary with location in the deposit (fig. 12A). In the black schist ore the Ag/Au ratio is highest (average 170-400) and gold content lowest (Au, about 0.005 oz per ton). In massive sulfide ore the Ag/Au ratio decreases to 30-100 (average for unoxidized ore about 55) and the gold grade increases to about 0.04 oz per ton. Chert ore has the lowest Ag/Au ratio (30) and the highest gold grade (0.10 oz per ton). Positive correlations of gold with zinc and gold with combined zinc and copper are noted for massive sulfide ore (fig. 12B, C, table 3). The best correlation between precious and base metals in massive and siliceous massive sulfide ore is between gold and combined copper plus zinc (0.570 for 106 samples). Except for data from the 3000 level the correlation between zinc and gold is as good or better than that between gold and combined zinc plus copper (table 3). Gold distribution is not well correlated with copper except on the 3000 level. The addition of silver to gold decreases the correlation with combined copper plus zinc, indicating that silver must be present in another mineral in addition to the assumed electrum, most reasonably galena.

CONCLUSIONS

Distinguishing Characteristics

The deposit at the United Verde mine is very typical of Archean, Proterozoic, and Phanerozoic volcanogenic massive sulfide deposits (Ohmoto and Skinner, 1983; Franklin, Lydon, and Sangster, 1981; Sangster, 1980 and 1972; Ishihara, 1974; Hutchinson, 1973; and Gilmour, 1965). The ore body occurs at the top of a submarine rhyolite dome and flow breccia unit (Cleopatra quartz porphyry member of the Deception rhyolite; Anderson and Nash, 1972) that is part of and overlies a predominantly calc-alkalic, low- to medium-K, iron-rich suite rhyolite to basalt. The deposit is zoned from top to bottom and consists of capping chert and siliceous massive sulfide ore, pyrite-rich massive sulfide, zinc- and copper-zinc-rich massive sulfide, chloritic stringer ore and chloritized Cleopatra quartz porphyry ore. Gold and silver are present in all ore types but are concentrated at the stratigraphic top, in massive sulfide, siliceous massive sulfide (both zinc- and copper-rich), and chert ore. The grade of precious metals in the deposit (Au, 0.041 oz per ton; Ag, 1.49 oz per ton) is comparable to other volcanogenic massive sulfide deposits in Arizona (DeWitt, 1983) and was exceeded only by the Iron King mine near Humboldt, Arizona (Au, 0.073 oz per ton; Ag, 2.67 oz per ton; Arizona Bureau of Geology and Mineral Technology, unpublished production data). The deposit is the largest known volcanogenic massive sulfide in the United States (33 million tons mined; minimum of 50-70 million tons of low-grade material remaining) and one of the largest in North America. Only the Kidd Creek (Walker and others, 1975) and Brunswick 12 deposits (Sangster, 1984; McAllister and others, 1980) have greater reserves plus production tonnages.

Ore Controls

The localization of the stratiform massive sulfide body was controlled by a hydrothermal conduit now represented by the chlorite schist and chloritic alteration pipe in the Cleopatra quartz porphyry. No paleotopographic controls, such as basins, sides of domes, etc., have been recognized in the Jerome area although they could have existed and have been masked by the deformation of the metavolcanic rocks. Why such a large sulfide body was localized at the top of the Cleopatra quartz porphyry, as opposed to lower in the volcanic pile, is unknown, but the genesis of the deposit must have been intimately associated with the evolution of the submarine volcanic suite.

The deposit is overlain by a sequence of volcaniclastic sediment, tuff, cherty sediment, and jasper-rich beds (Grapevine Gulch formation) that is compositionally unlike the underlying flows, breccias, domes, and intrusives. Therefore, formation of the massive sulfide deposit appears to have marked the end of the period of submarine calc-alkalic volcanic activity and signaled the beginning of volcaniclastic activity that was chemically more evolved (alkali-calcic nature?) and was certainly of a different nature (partly subaerial; tuff and immature sedimentary rock dominant instead of flows).

Base and precious metals are zoned within the deposit; the alteration pipe contained average to high copper but very little zinc, gold, or silver. The massive sulfide body had average to high copper, zinc, gold, and silver. The capping siliceous massive sulfide horizon and chert layers had base and precious metal contents similar to the highest massive sulfide ores. If all the metals were transported through the alteration pipe to the paleosurface by hydrothermal solutions, zinc and gold were retained in solution longer than copper and silver, and were precipitated only upon reaching the seawater-sediment interface. This zonation is consistent with decreased pH, Eh, and temperature of the hydrothermal solution at the inferred top of the deposit.

Origin

The United Verde deposit was formed in a Proterozoic submarine environment during deposition of rhyolite flows, tuffs, and pyroclastic material. The massive sulfide body and underlying chloritic alteration pipe are the end products of hydrothermal solutions enriched in copper, zinc, lead, gold, and silver that traveled up and through the Cleopatra quartz porphyry and ultimately precipitated their sulfide minerals at the seawater interface. Chemical studies have not been completed that would indicate the ultimate source of metals in the deposit, whether that source be the underlying volcanic pile (leaching and redistribution of metals) or the magma reservoir of the Cleopatra quartz porphyry (primary enrichment of metals in the magma).

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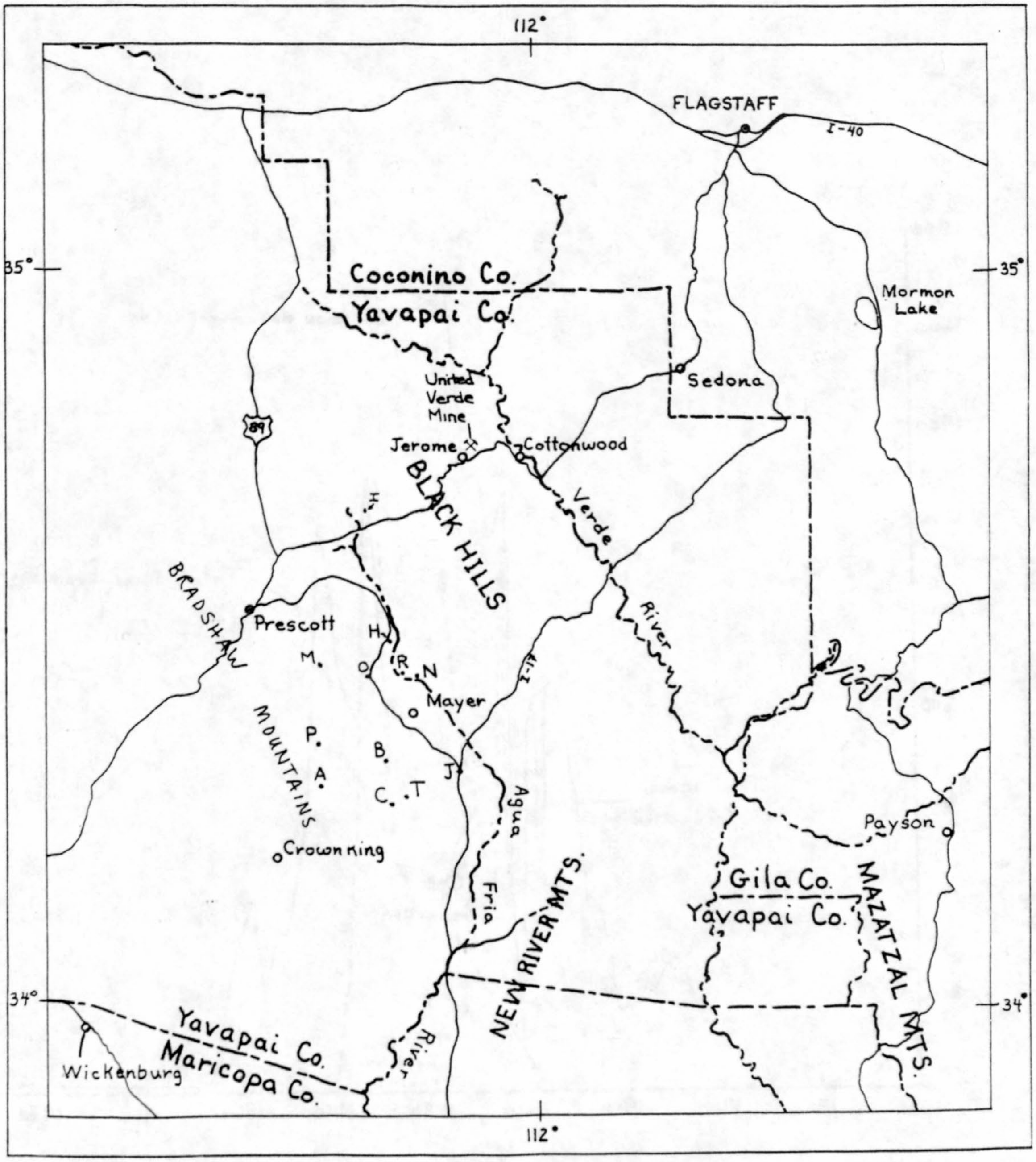

Figure 1. Location map of the Jerome area, north-central Arizona. Localities mentioned in text include A, Battle Flat; B, Bluebell mine; C, Cleator; H, Humboldt; I, Indian Hills,; J, Cordes Junction; M, Mount Elliott; N, Binghampton mine; O, Poland Junction; P, Pine Flat; R, Bell Ranch; T, Townsend Butte.

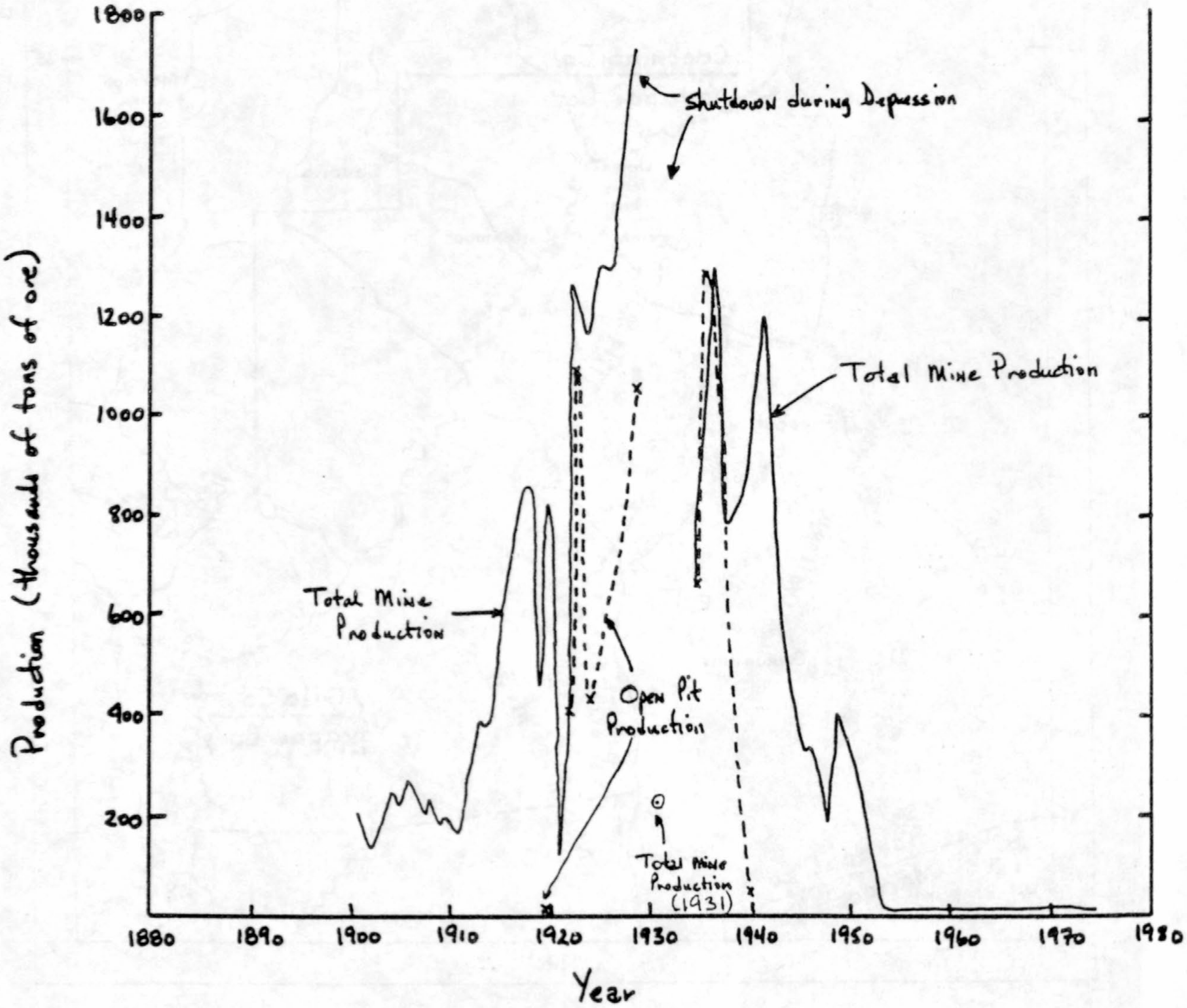

Figure 2A. Plot of production vs time during the lifetime of the United Verde mine. Data from Table 1 and unpublished data from the Arizona Bureau of Geology and Mineral Technology.

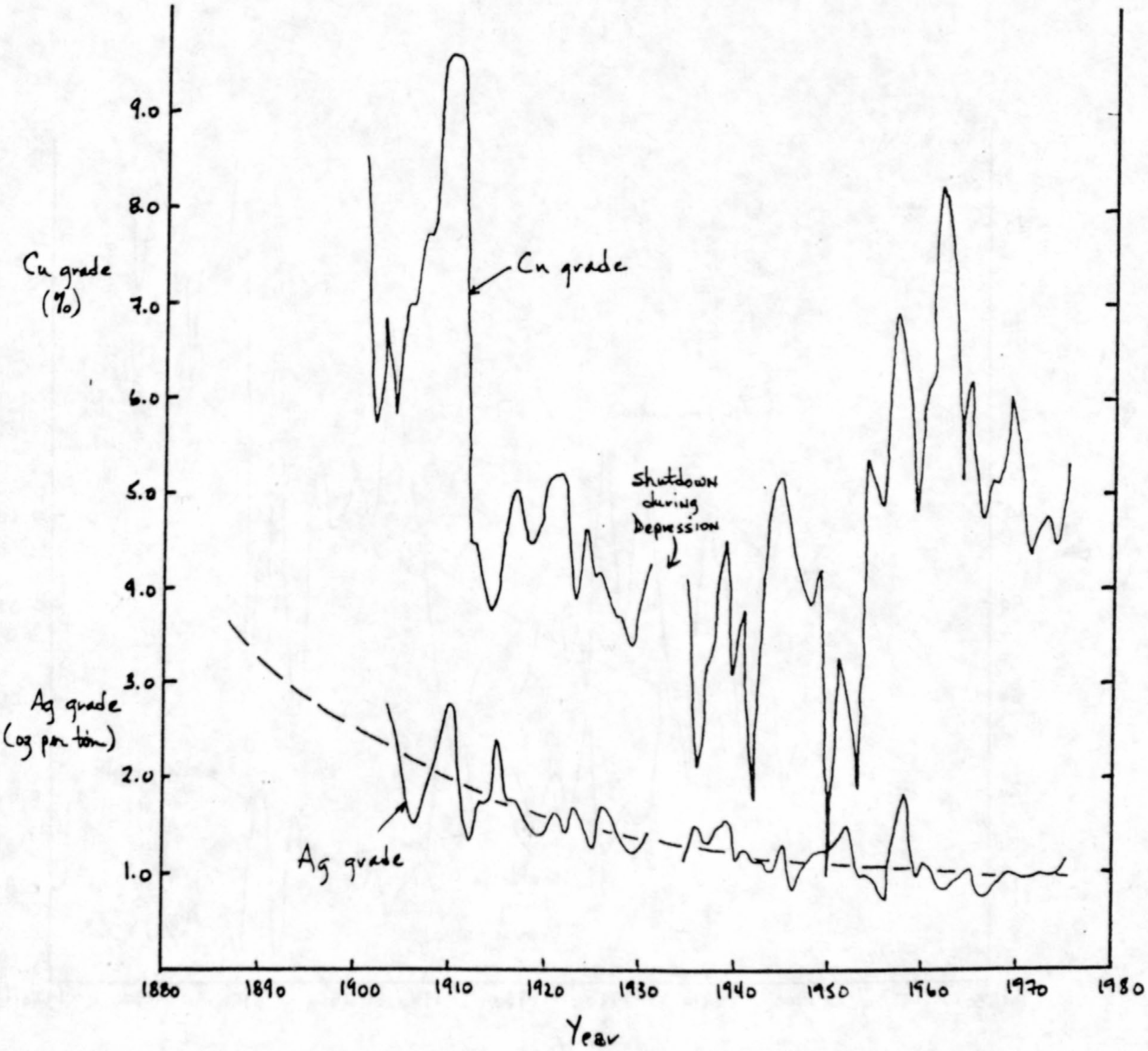

Figure 2B. Plot of copper and silver grades vs time during the lifetime of the United Verde mine. Data from Table 1 and unpublished data from the Arizona Bureau of Geology and Mineral Technology.

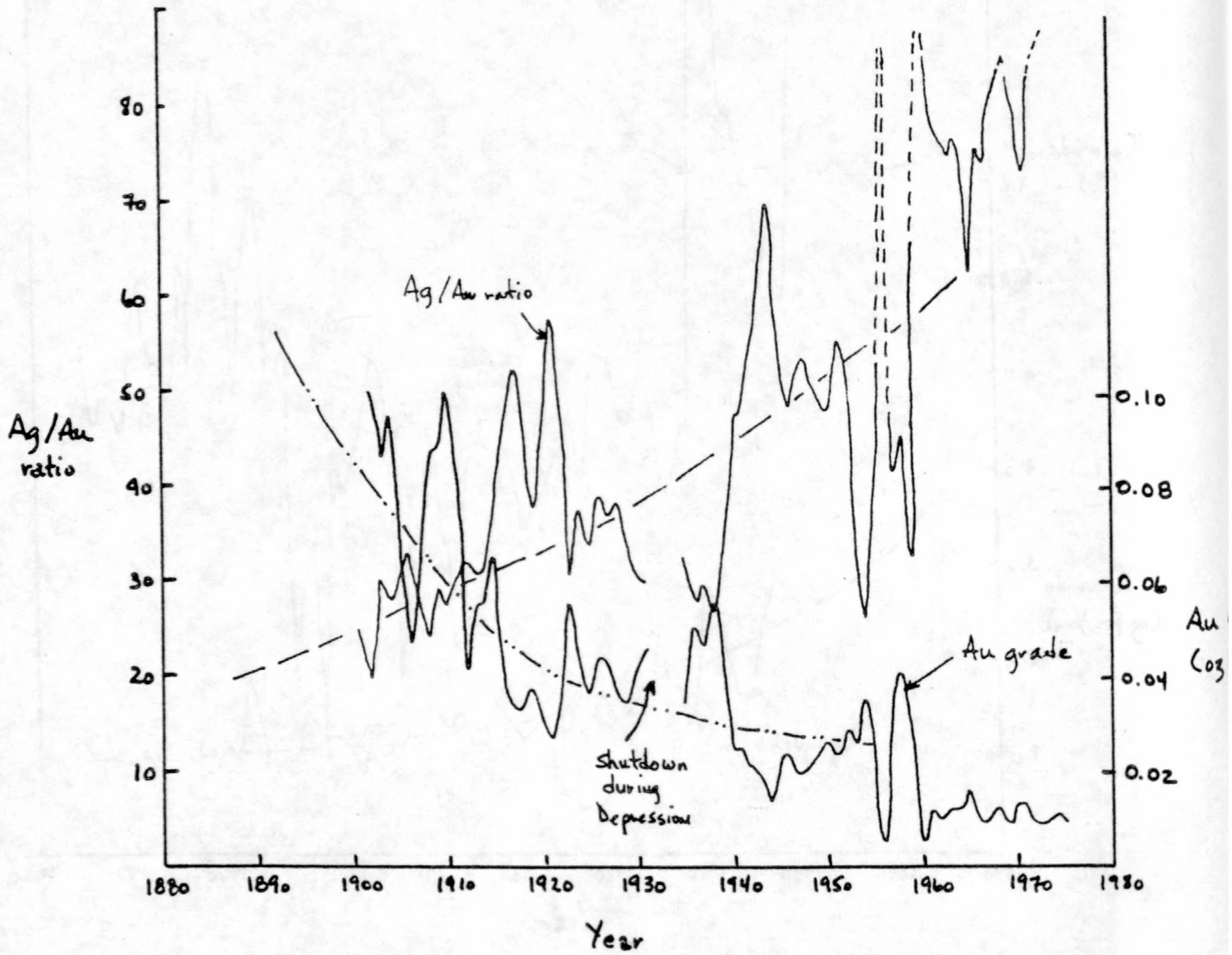

Figure 2C. Plot of Ag/Au and gold grade vs time during the lifetime of the United Verde mine. Data from Table 1 and unpublished data from the Arizona Bureau of Geology and Mineral Technology.

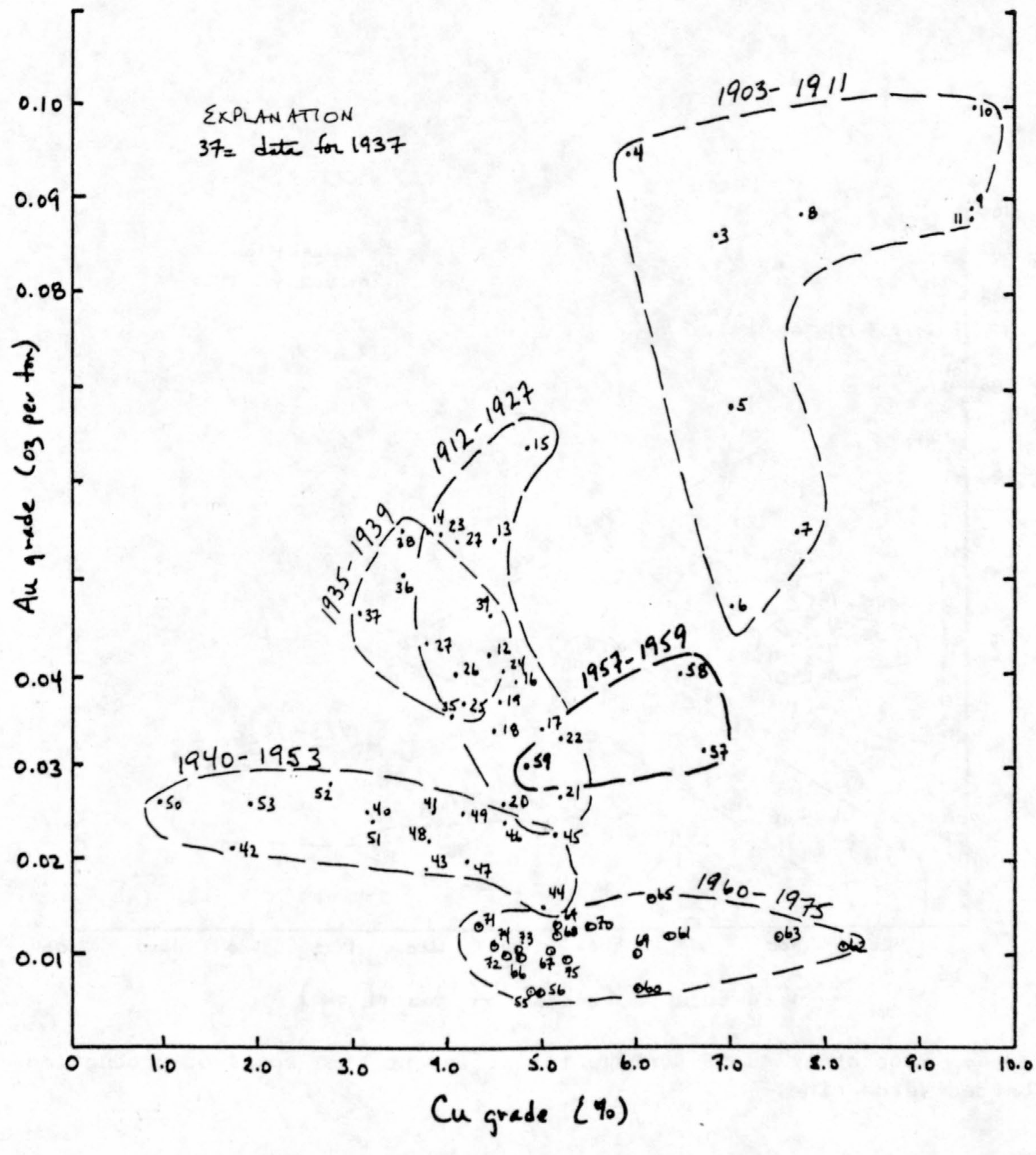

Figure 3. Plot of gold vs copper for different time spans of production in the United Verde Mine.

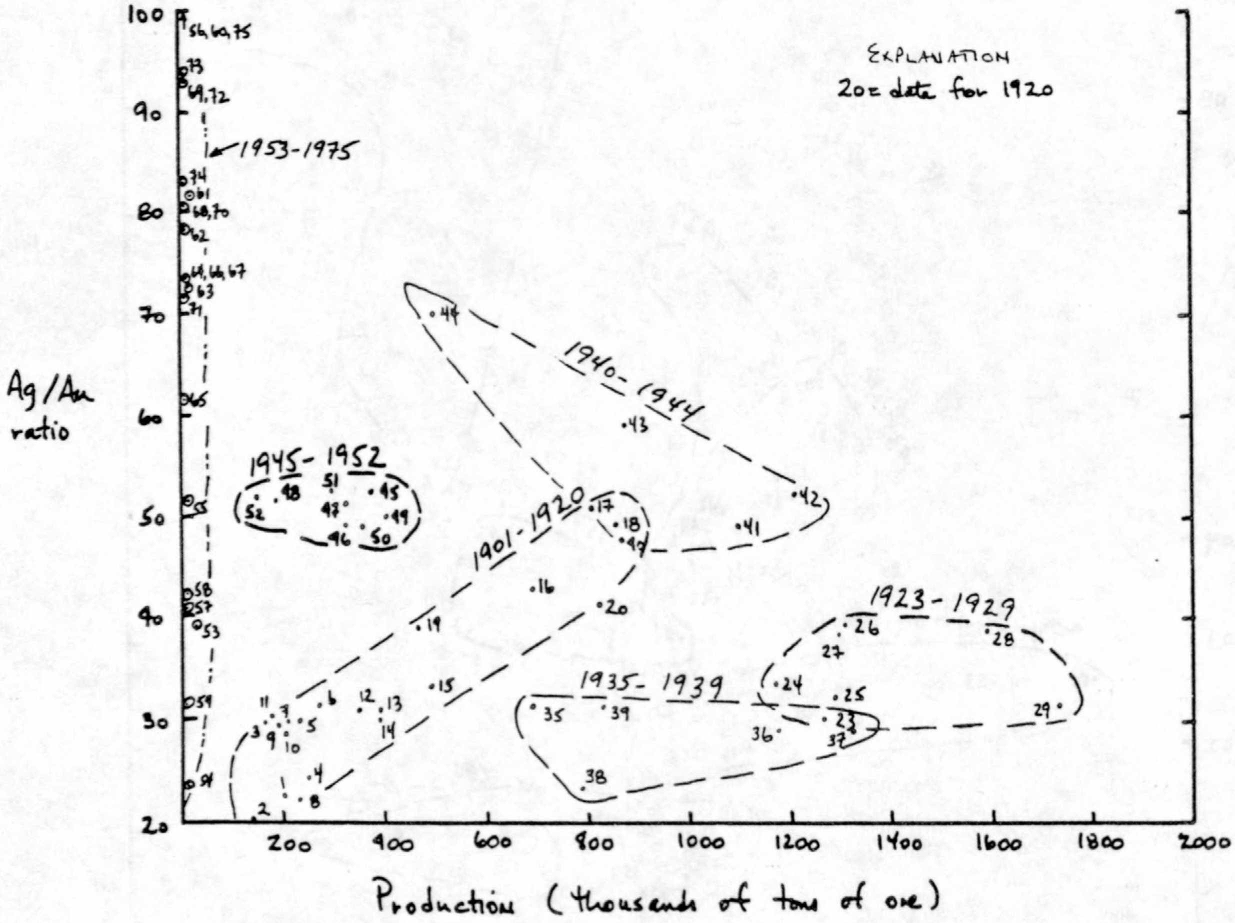

Figure 4. Plot of Ag/Au vs tonnage for different time spans of production in the United Verde mine.

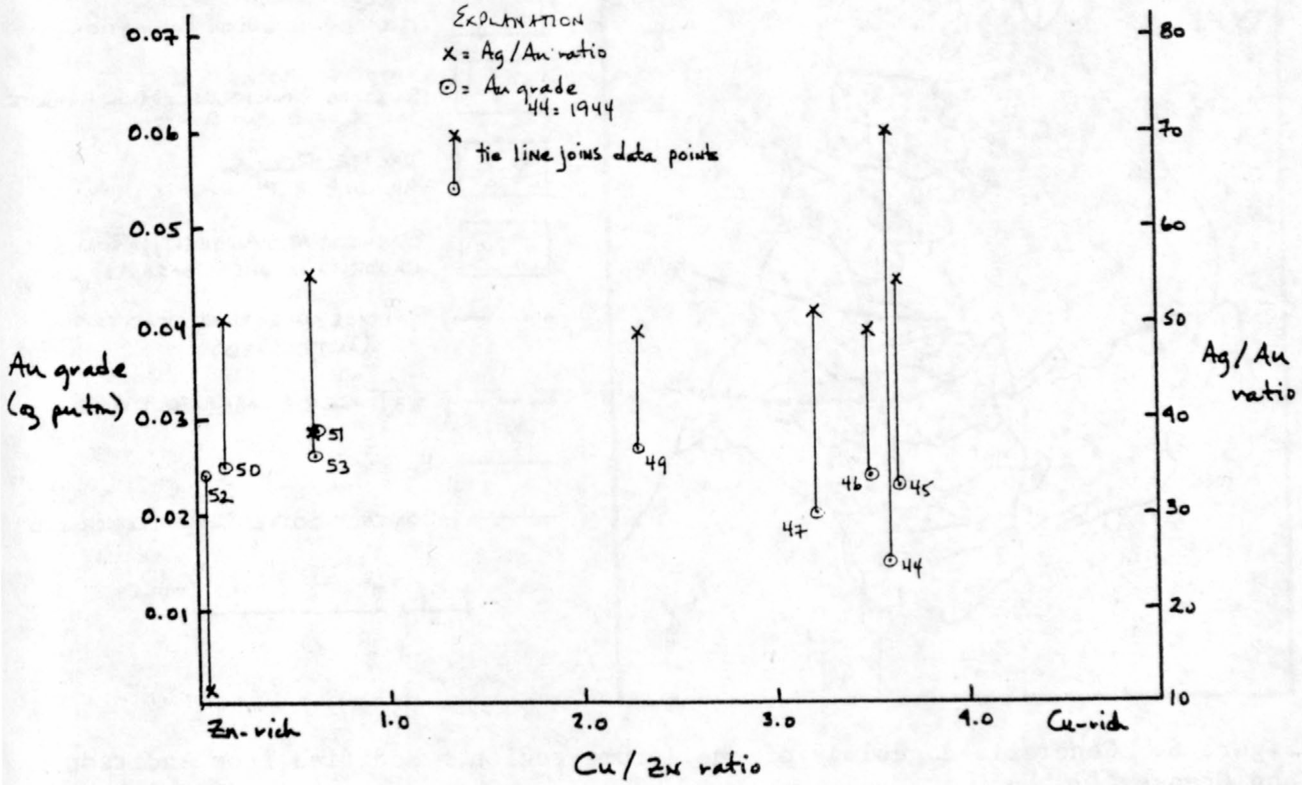

Figure 5. Plot of gold grade and Ag/Au ratio vs Cu/Zn ratios for ore mined from 1944 through 1953 from the United Verde Mine.

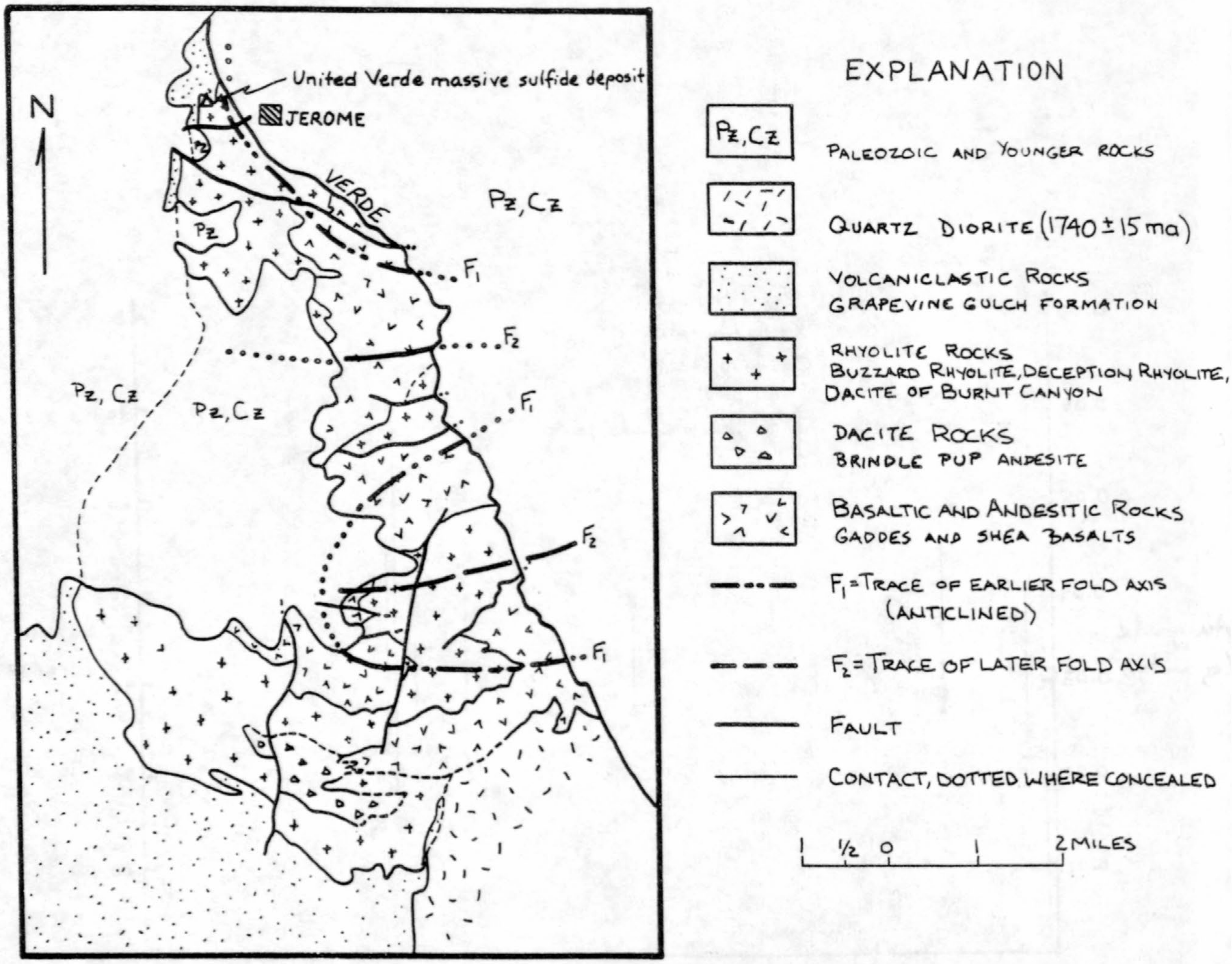

Figure 6. Generalized geology of the Jerome region. Modified from Anderson and Creasey (1958).

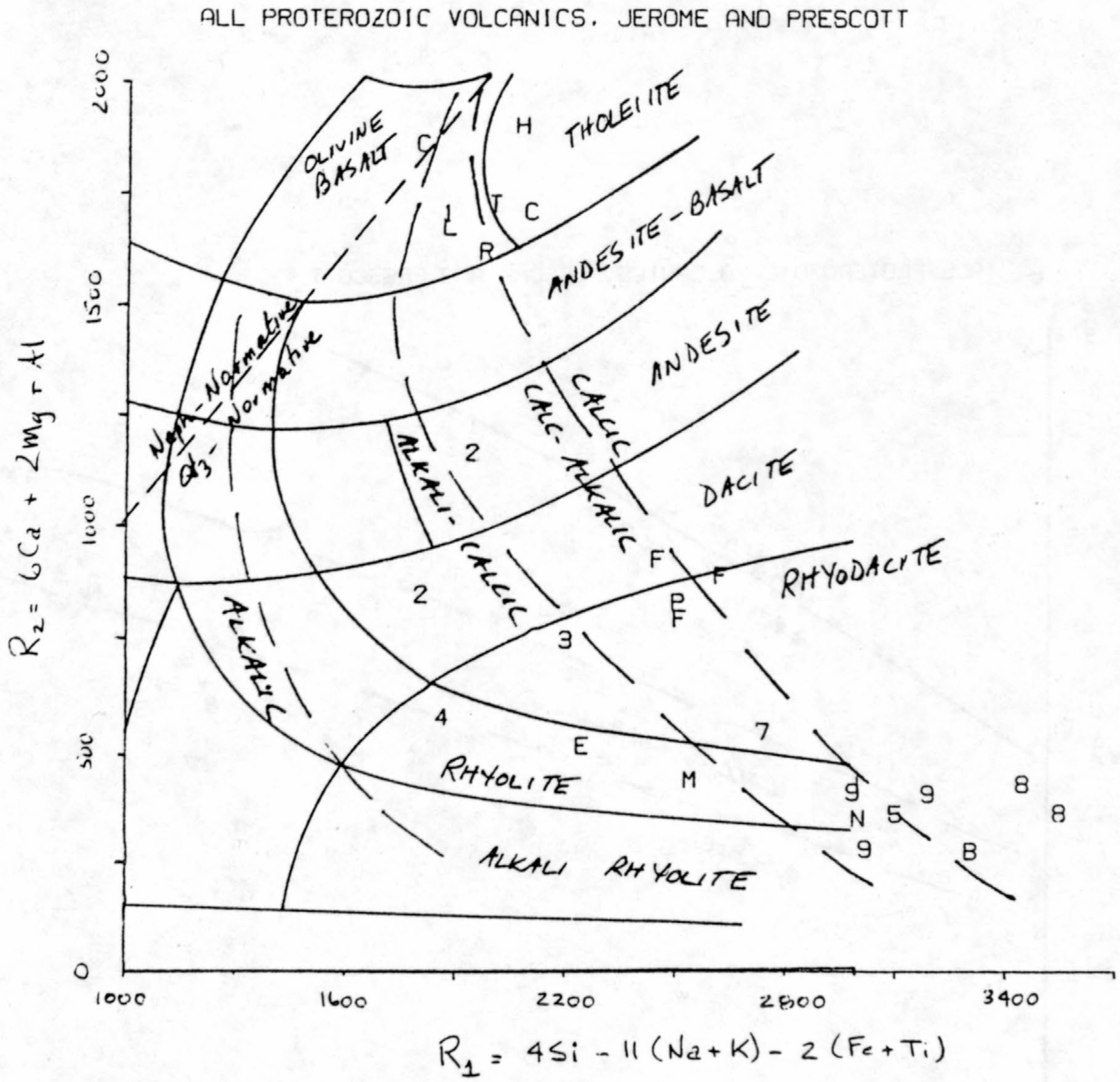

Figure 7. Chemical classification diagram (De la Roche and others, 1980) for volcanic units in the Jerome and Prescott areas. Data from Anderson and Creasey (1958), Anderson and Blacet (1972), Krieger (1965), and Vrba (1980). Only those analyses (in weight percent) are plotted that contain less than 3.0 percent H_2O, less than 1.0 per cent CO_2, and have total oxide weight percents between 98.5 and 100.5 percent. Numbers designate rock units in the Jerome area: 1, gabbro at United Verde mine; 2, Shea Basalt; 3, Brindle Pup Andesite; 4, dacite from Grapevine Gulch Formation; 5, Buzzard Rhyolite; 7, dacite of Burnt Canyon; 8, Cleopatra quartz porphyry; 9, other quartz porphries probably correlative with Cleopatra. Letters designate rock units in the Prescott area: B, rhyolite near the Binghampton mine; C, basalt northwest of Cleator; E, rhyolite near Mt. Elliott; F, andesite near Pine Flat and Battle Flat; H, basalt near Humboldt; J, rhyolite near Cordes Junction; L, basalt near Bluebell mine; M, basalt near Mayer; N, rhyolite near Indian Hills; P, andesite west of Poland Junction; R, basalt near the Bell ranch, southeast of Humboldt; T, basalt near Townsend Butte, east of Cleator. Approximate boundaries between calcic, calc-alkalic, alkali-calcic, and alkalic suites shown by heavy, dashed lines.

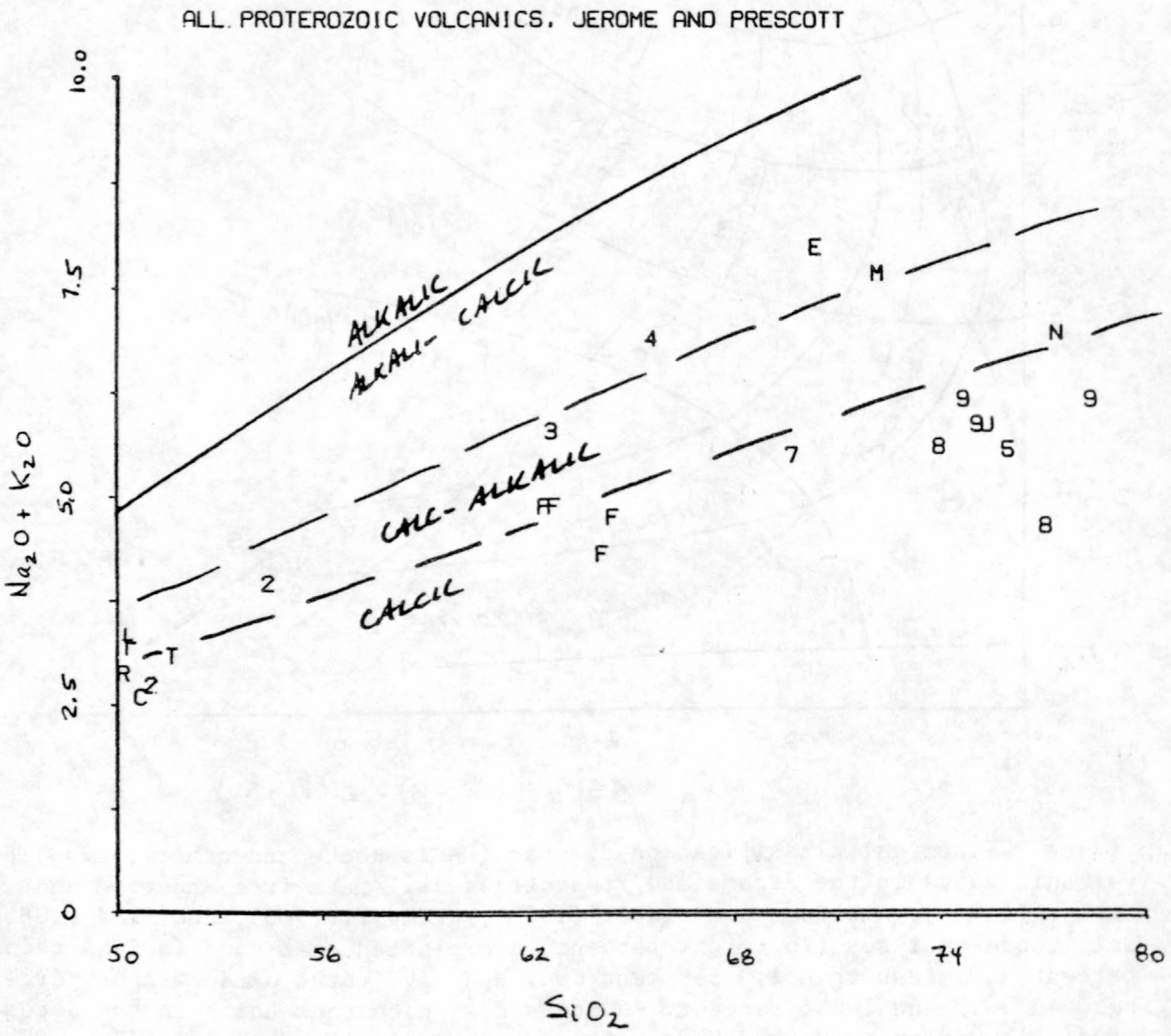

Figure 8A. $Na_2O + K_2O$ versus SiO_2 (in weight percent) diagram for volcanic rocks in the Jerome and Prescott areas. Sources of data as on figure 7. Alkalic versus alkali-calcic field boundary from Anderson (1983); other field boundaries extrapolated from Gill (1981) and Ewart (1979). Symbols as on figure 7.

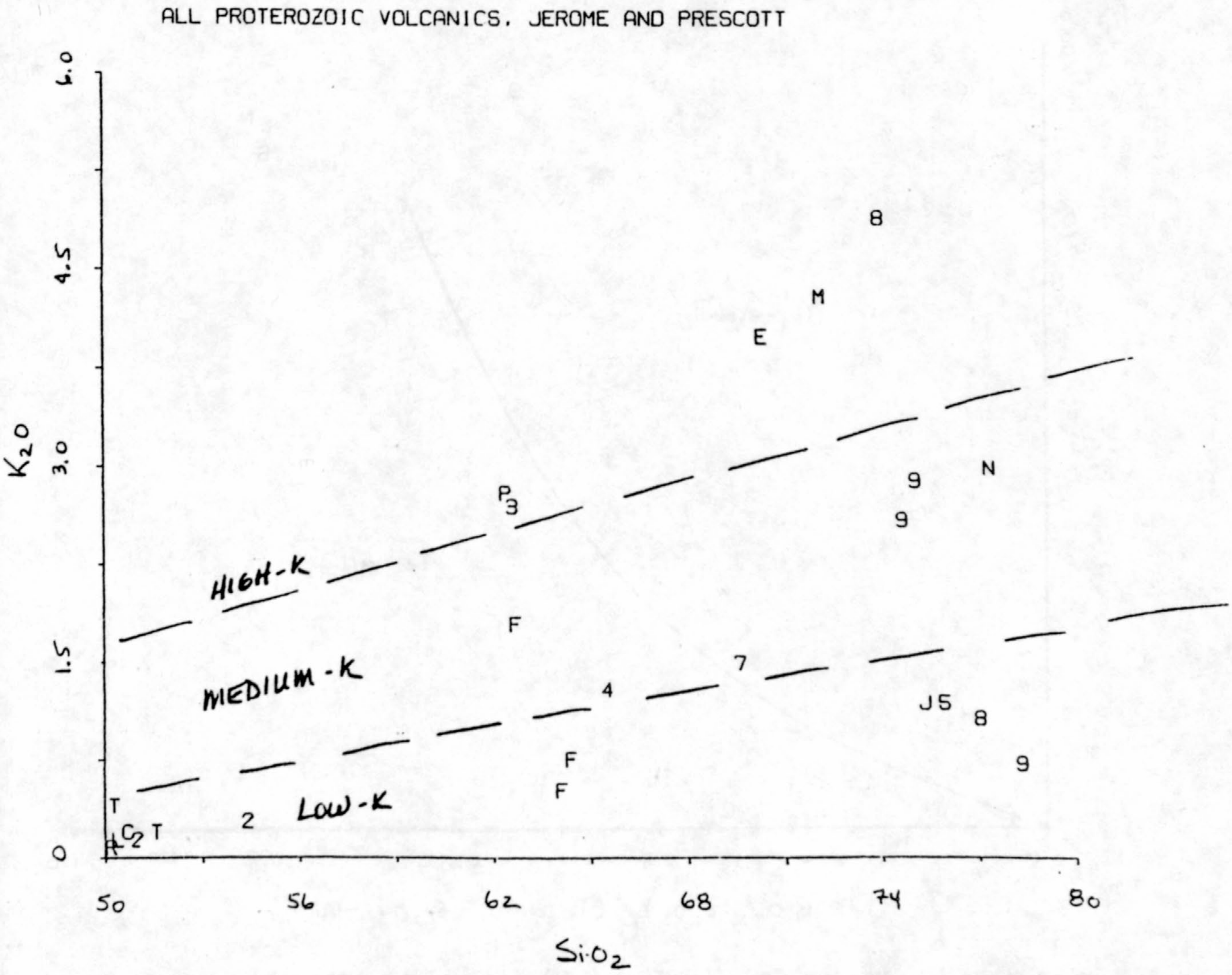

Figure 8B. K_2O versus SiO_2 (in weight percent) diagram for volcanic rocks in the Jerome and Prescott areas. Sources of data and symbols as on figure 7. Boundaries for low-, medium-, and high-K fields from Peccerillo and Taylor (1976).

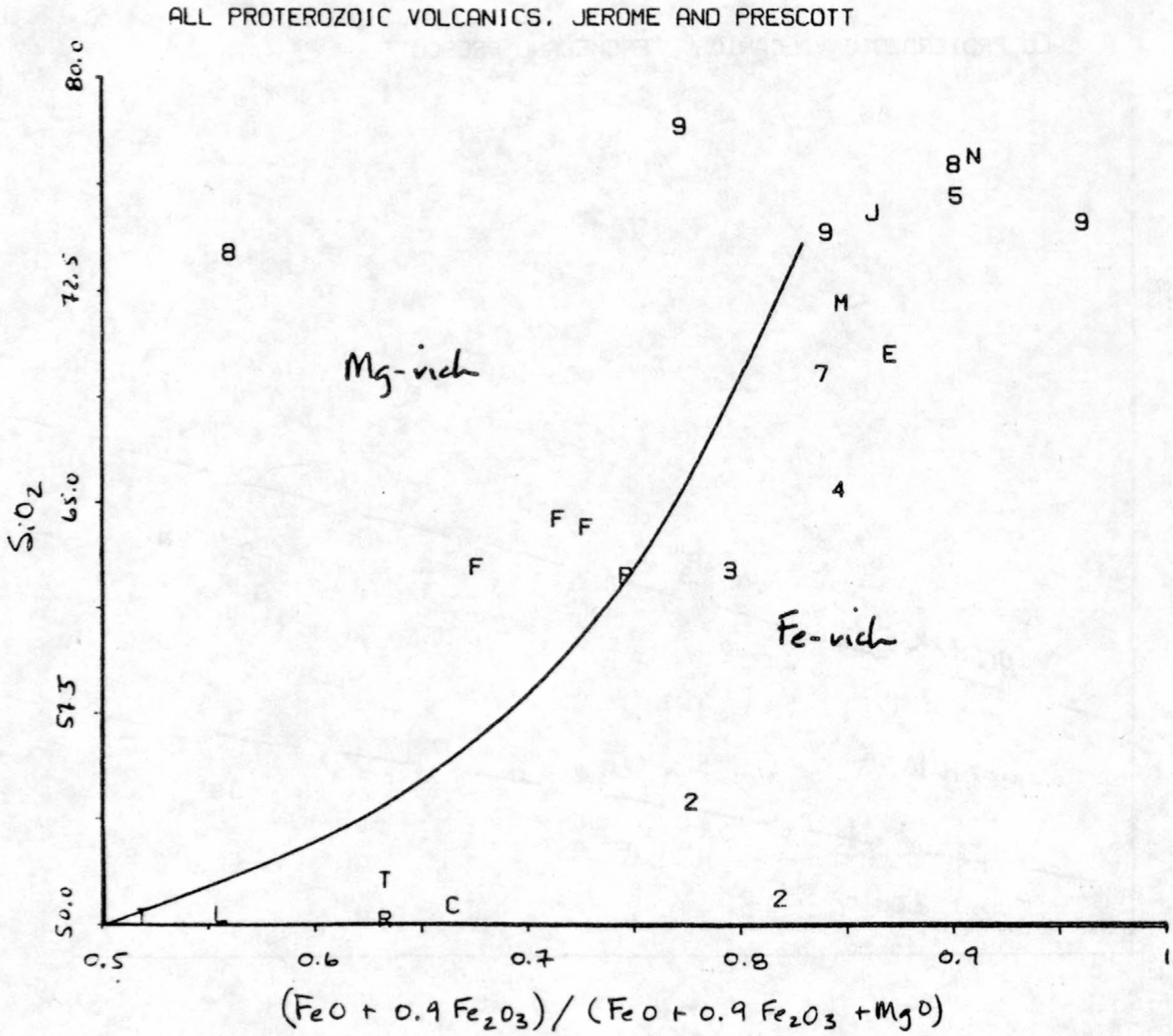

Figure 9. SiO_2 versus $FeO_t/(FeO_t + MgO)$ (in weight percent) diagram for volcanic rocks in the Jerome and Prescott areas. Sources of information and symbols as on figure 7. Boundary separating iron-rich from magnesium-rich fields is the boundary separating tholeiitic from calc-alkalic rocks, respectively, in Miyashiro (1974).

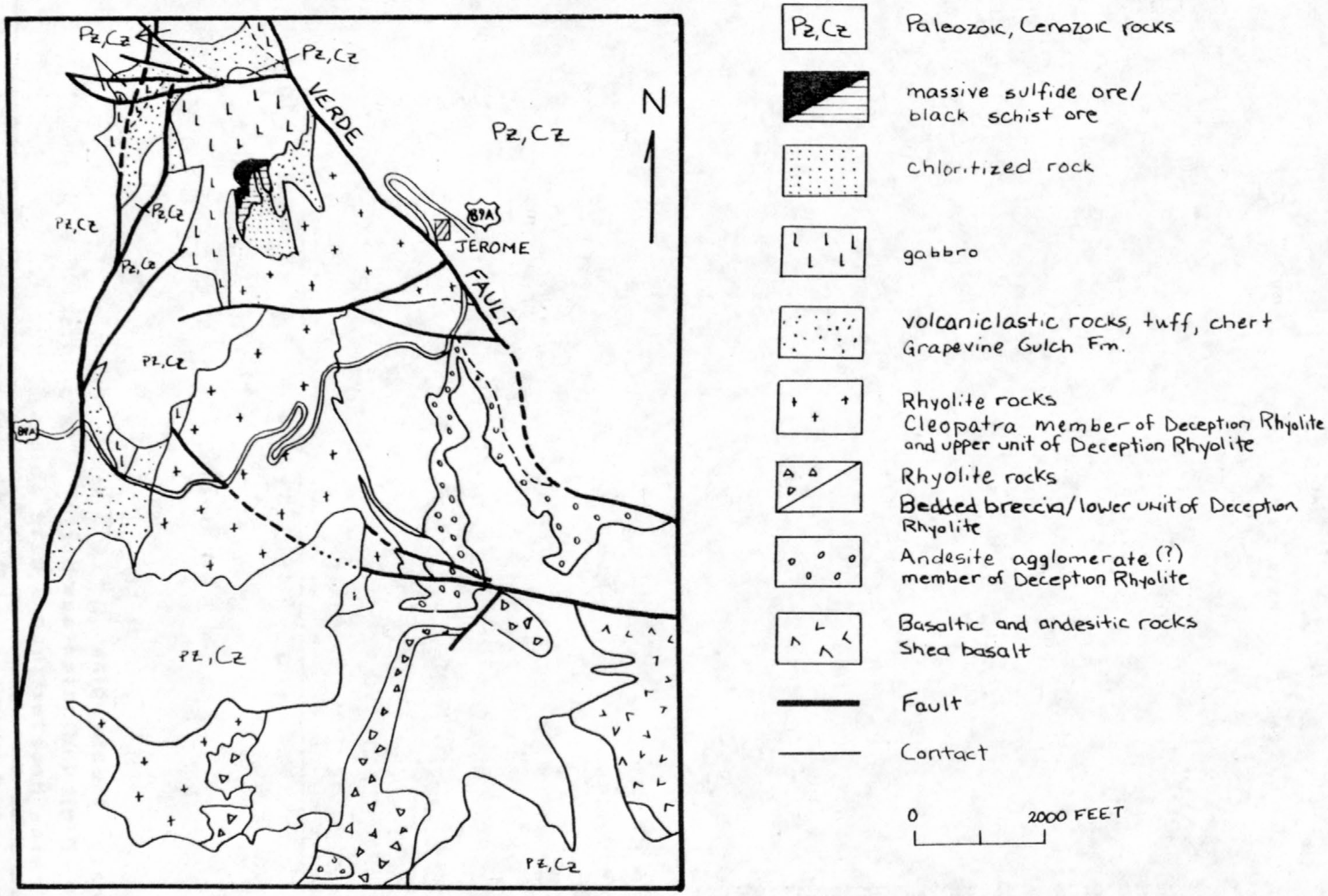

Figure 10. Geology of the United Verde Mine area. Modified from Anderson and Creasey (1958) and Lindberg and Jacobsen (1974).

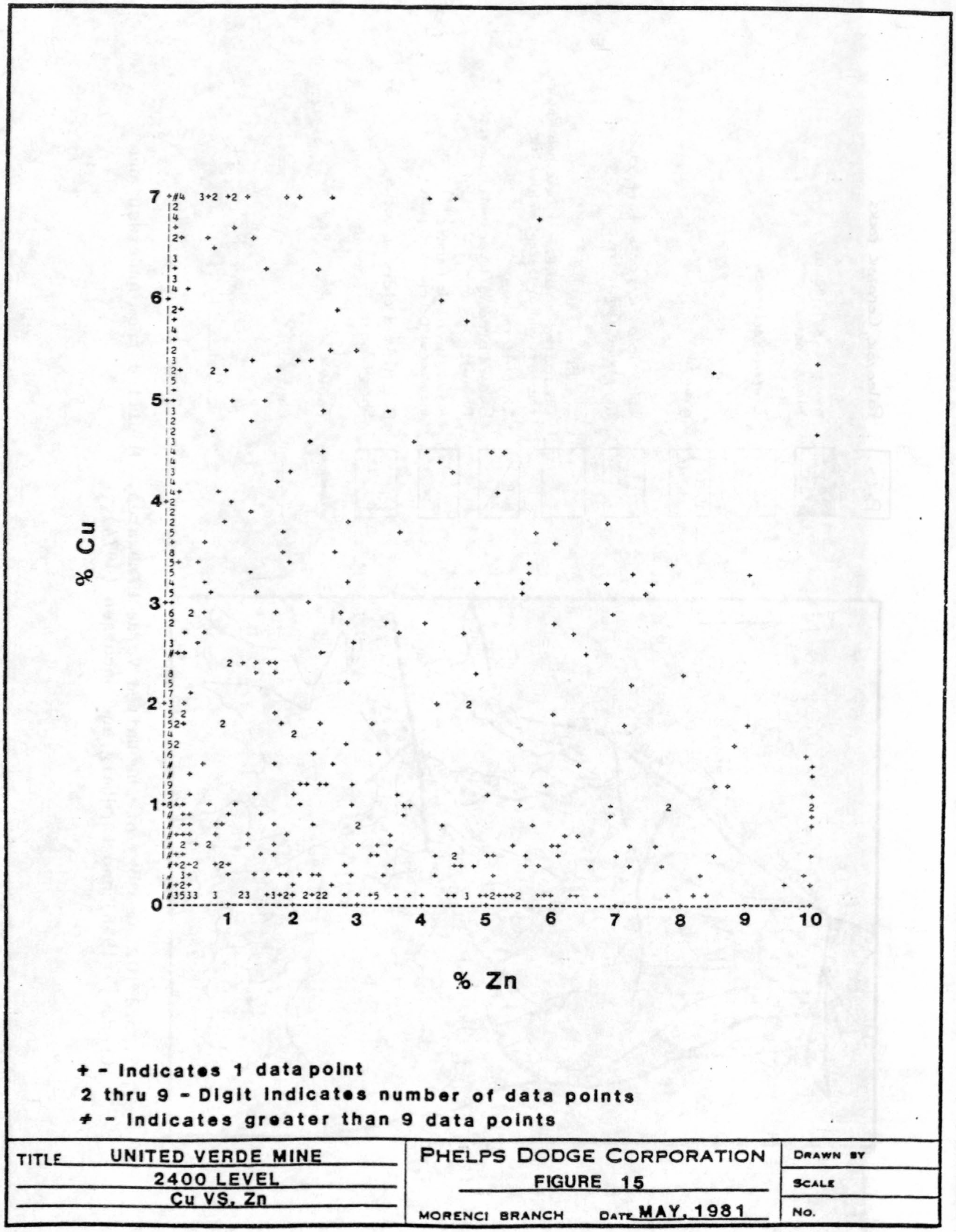

Figure 11A. Plot of Cu vs Zn for the 2400 level of the United Verde massive sulfide deposit. Data from unpublished assay results made available by Phelps Dodge Corporation. Individual ore types are not plotted separately. +, one analysis; 2-9, two or more analyses plot at one point; #, more than nine analyses plot at one point.

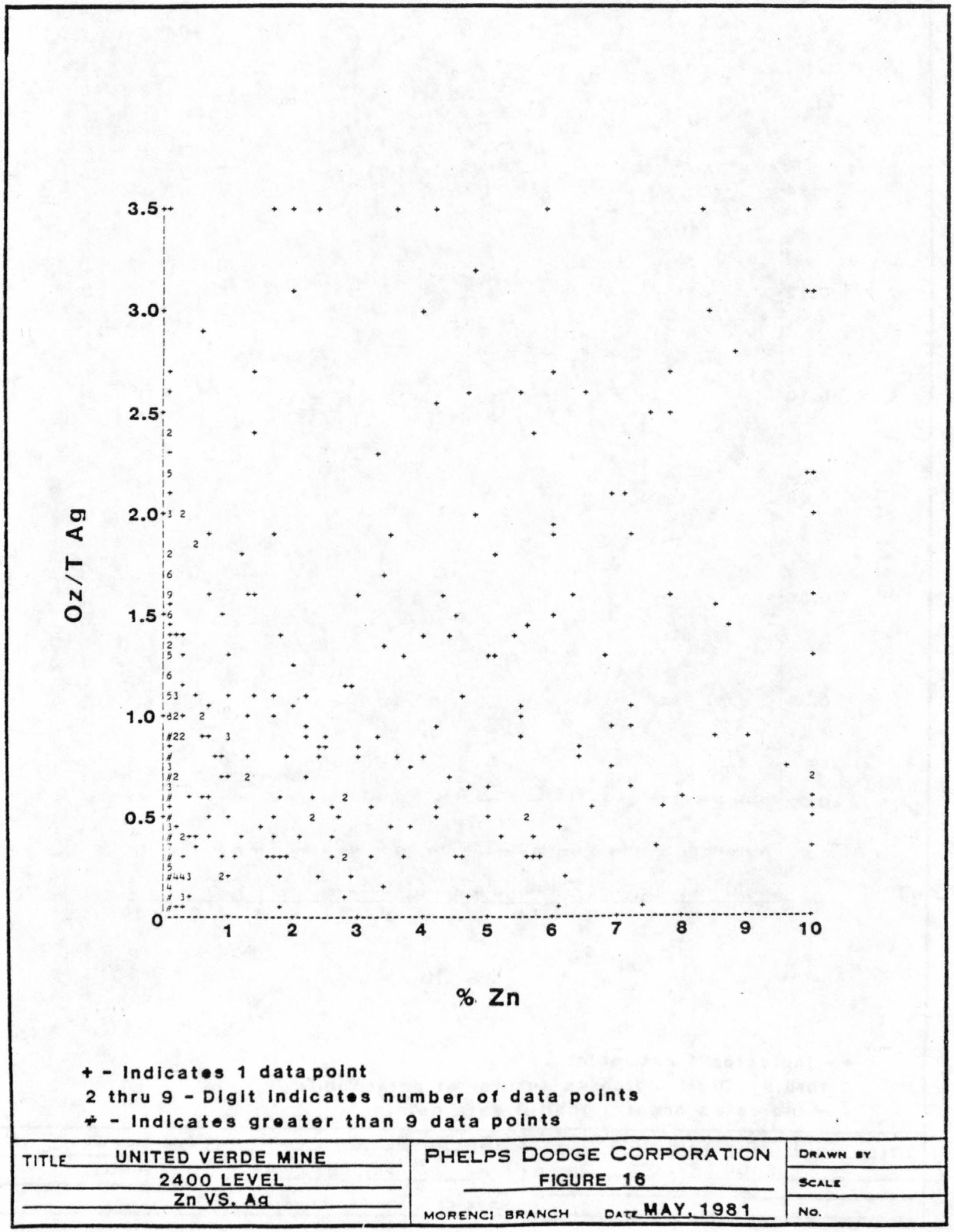

Figure 11B. Plot of Ag vs Zn for the 2400 level of the United Verde massive sulfide deposit. Data from unpublished assay results made available by Phelps Dodge Corporation. Individual ore types are not plotted separately. +, one analysis; 2-9, two or more analyses plot at one point; #, more than nine analyses plot at one point.

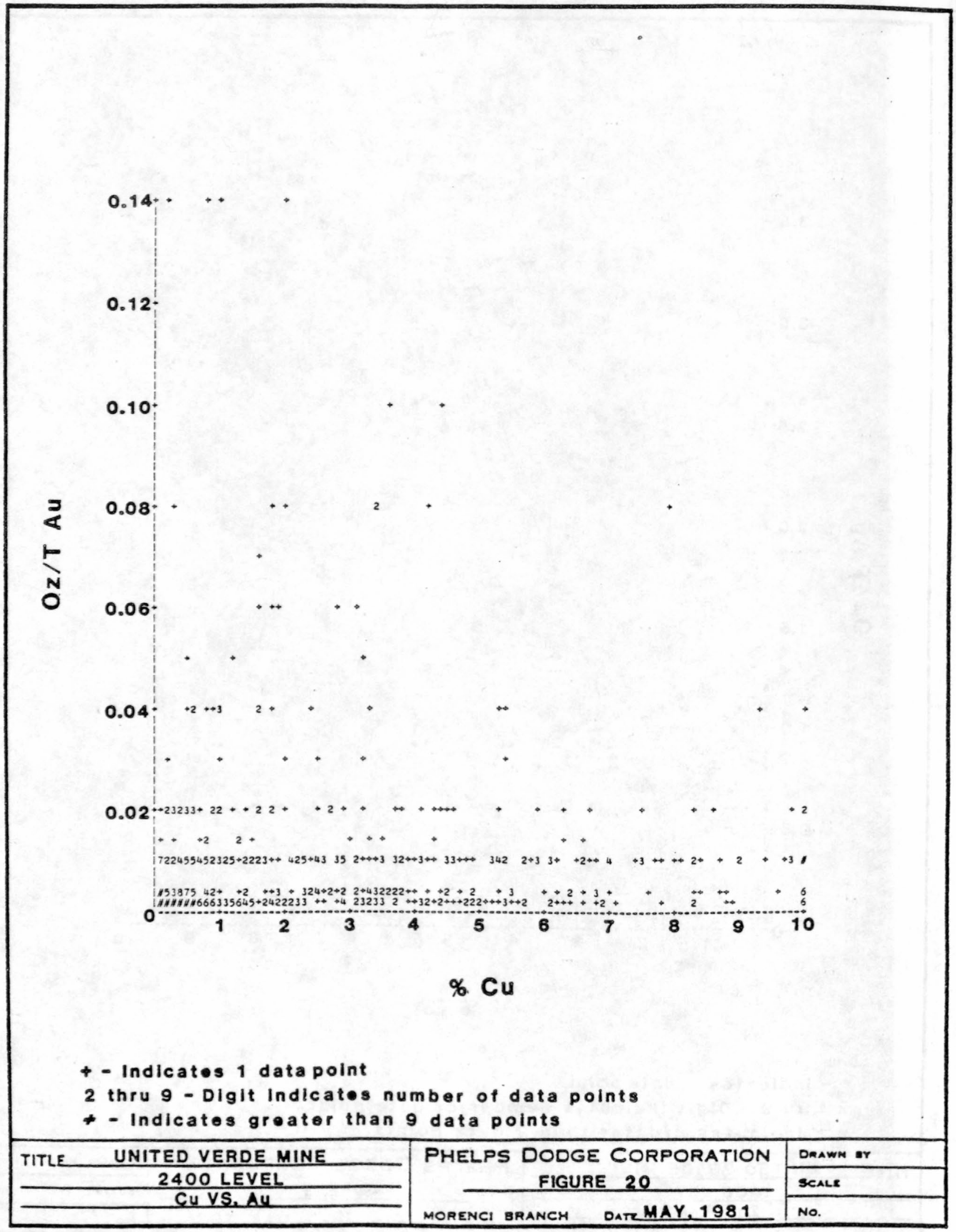

Figure 11C. Plot of Au vs Cu for the 2400 level of the United Verde massive sulfide deposit. Data from unpublished assay results made available by Phelps Dodge Corporation. Individual ore types are not plotted separately. +, one analysis; 2-9, two or more analyses plot at one point; #, more than nine analyses plot at one point.

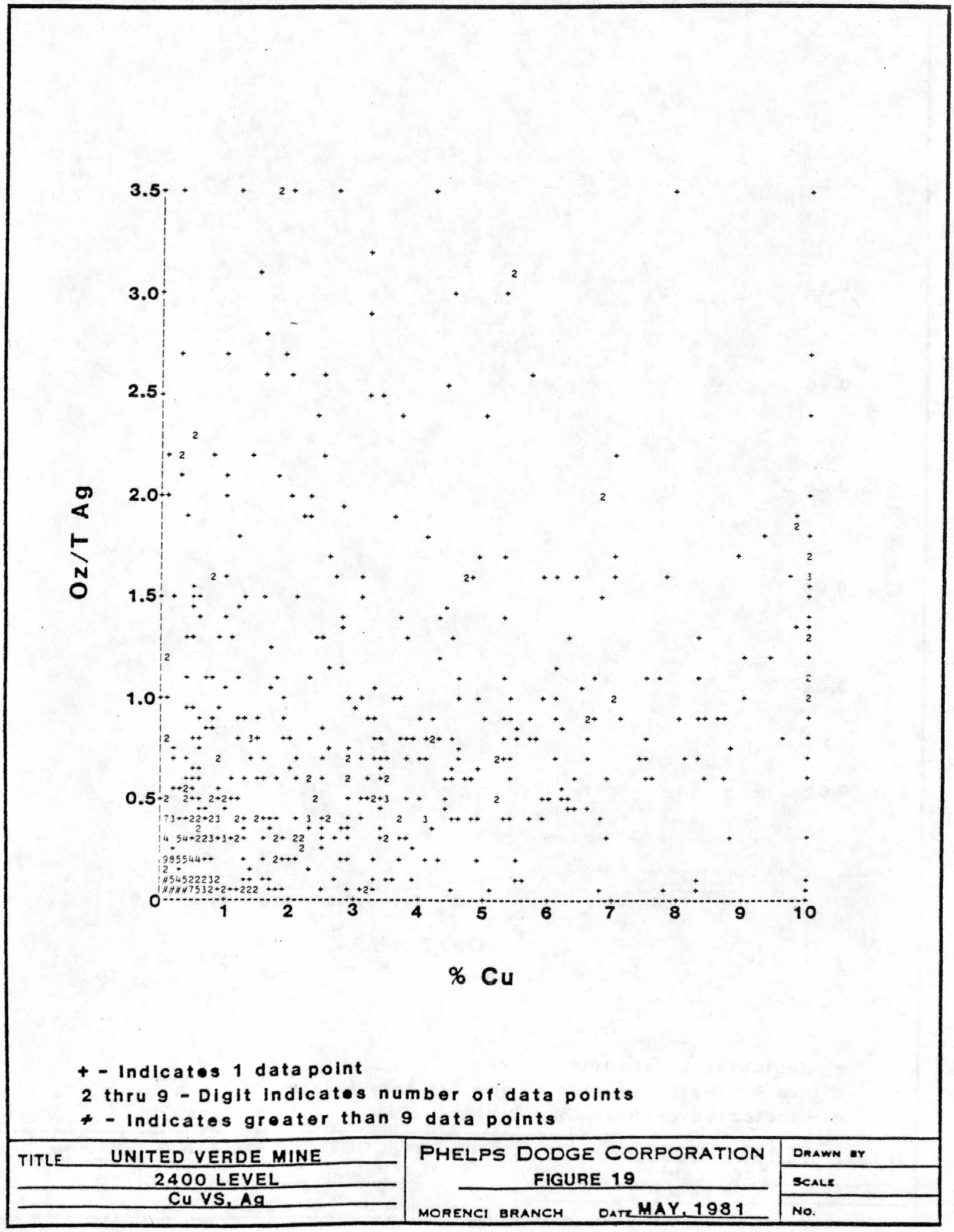

Figure 11D. Plot of Ag vs Cu for the 2400 level of the United Verde massive sulfide deposit. Data from unpublished assay results made available by Phelps Dodge Corporation. Individual ore types are not plotted separately. +, one analysis; 2–9, two or more analyses plot at one point; #, more than nine analyses plot at one point.

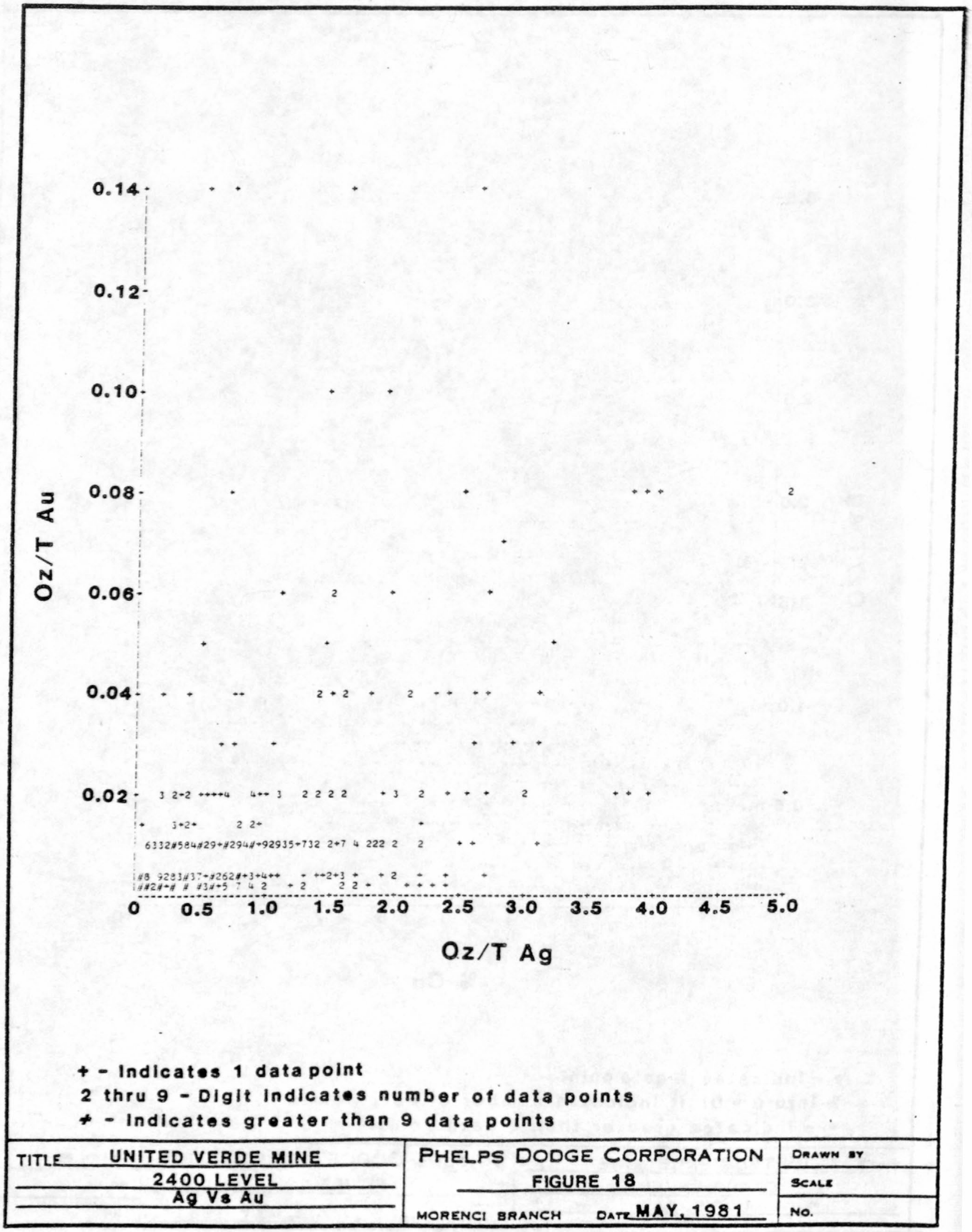

Figure 11E. Plot of Au vs Ag for the 2400 level of the United Verde massive sulfide deposit. Data from unpublished assay results made available by Phelps Dodge Corporation. Individual ore types are not plotted separately. +, one analysis; 2-9, two or more analyses plot at one point; #, more than nine analyses plot at one point.

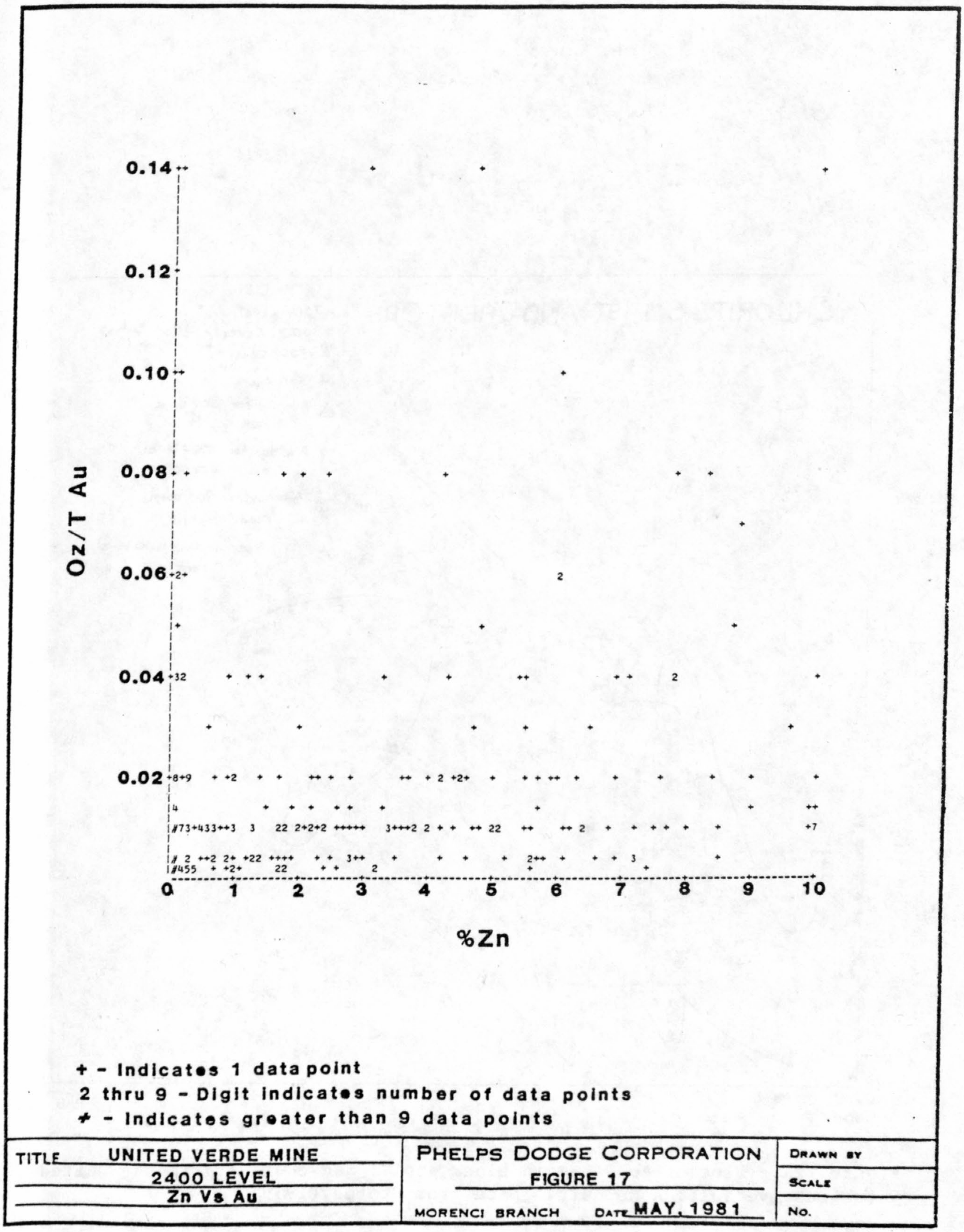

Figure 11F. Plot of Au vs Zn for the 2400 level of the United Verde massive sulfide deposit. Data from unpublished assay results made available by Phelps Dodge Corporation. Individual ore types are not plotted separately. +, one analysis; 2-9, two or more analyses plot at one point; #, more than nine analyses plot at one point.

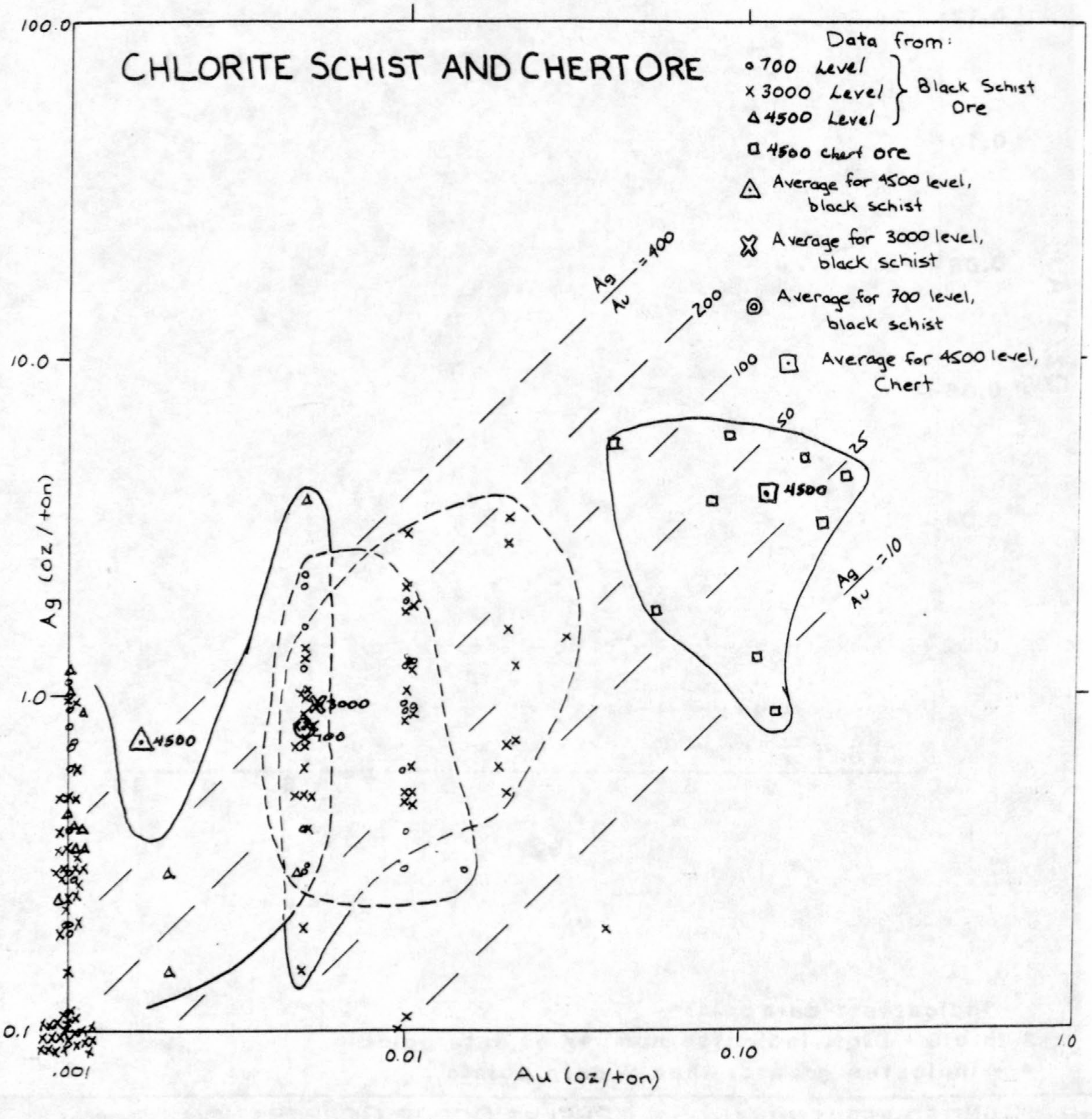

Figure 12A. Plot of Au vs Ag in black schist and chert ore in the United Verde massive sulfide deposit. Data from Storms (1955).

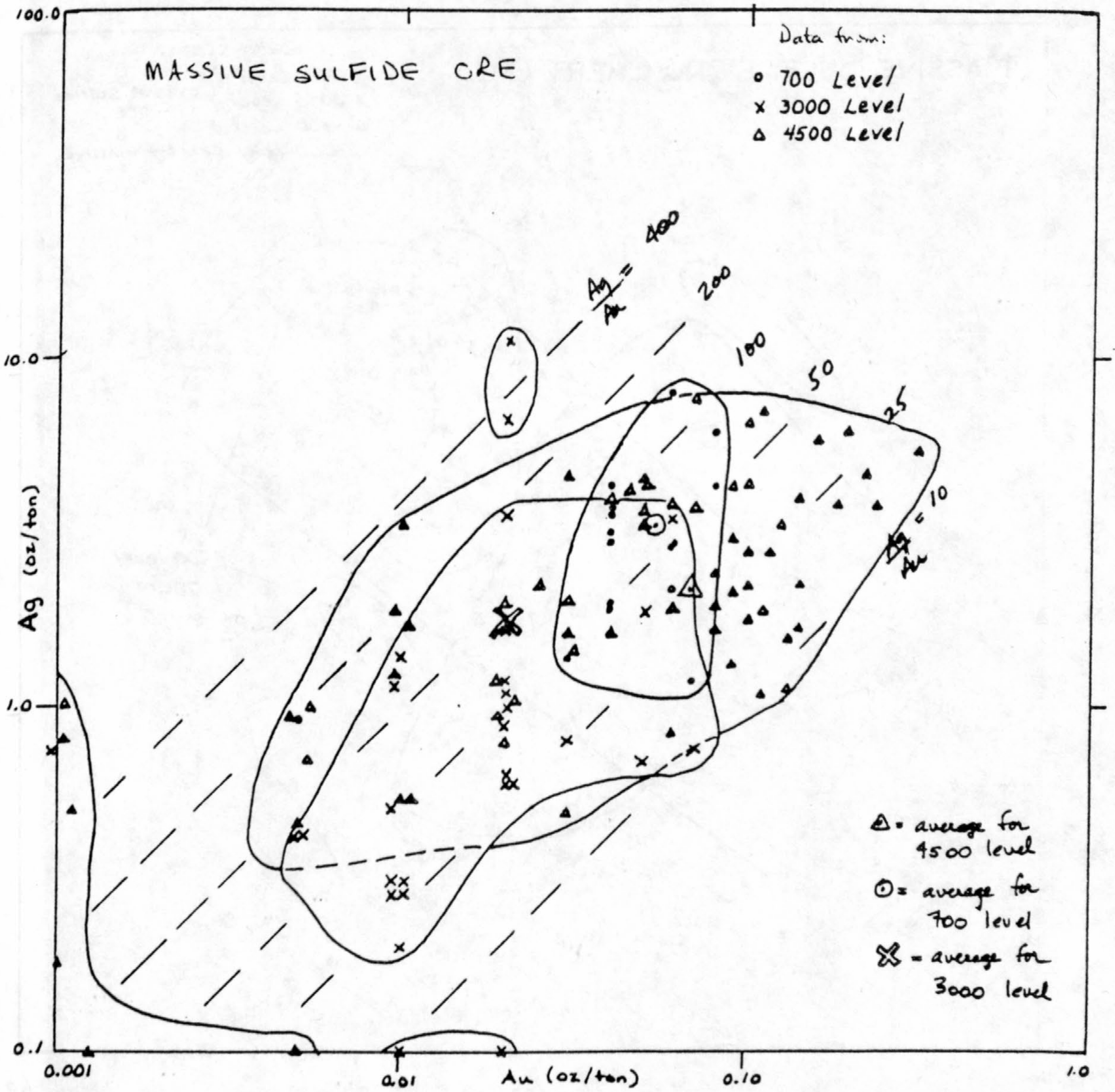

Figure 12B. Plot of Au vs Ag in massive sulfide ore in the United Verde massive sulfide deposit. Data from Storms (1955).

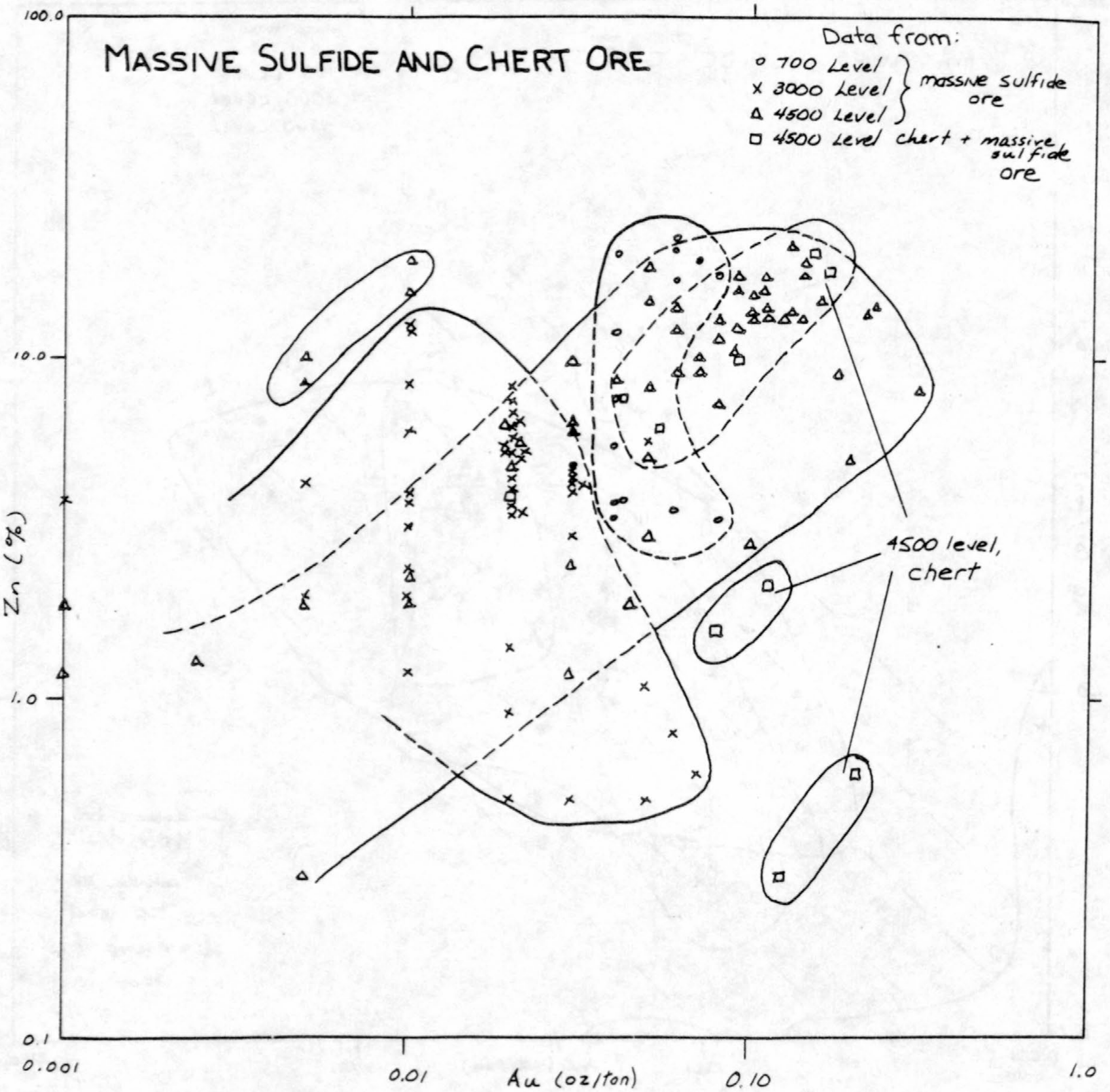

Figure 12C. Plot of Au vs Zn in massive sulfide and chert ore in the United Verde massive sulfide deposit. Data from Storms (1955).

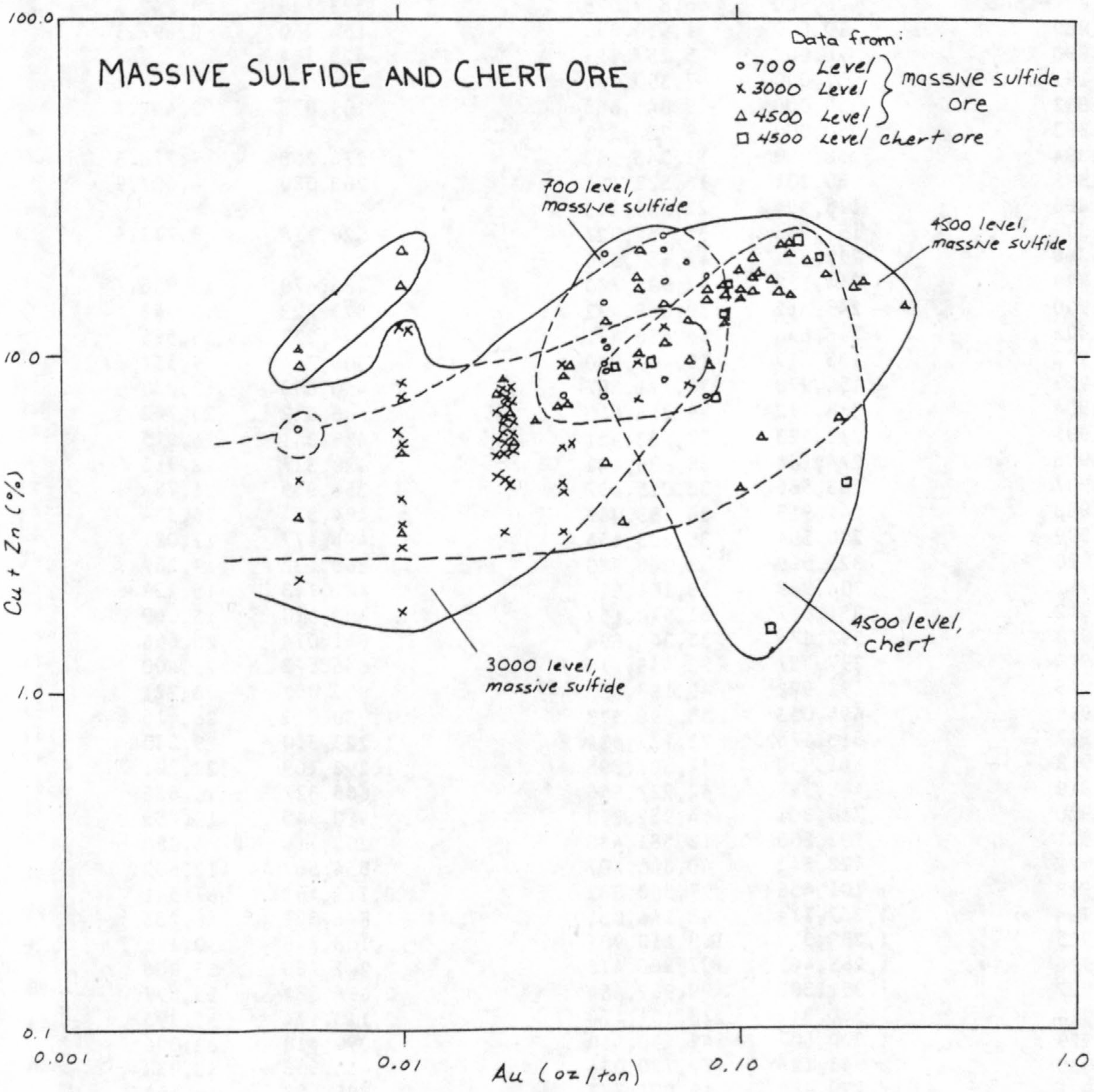

Figure 12D. Plot of Au vs Cu + Zn in massive sulfide and chert ore in the United Verde massive sulfide deposit. Data from Storms (1955).

Table 1. United Verde mine production records

[Data from Phelps Dodge Corporation except as footnoted. Production records for lead available only for 1884-1888 and 1975, from Arizona Bureau of Geology and Mineral Technology. U.V.--United Verde production; P.D.--Phelps Dodge production; Big Hole--composite of various small-scale leased operations]

Year	Tons Mined	Metals Recovered				
		Lbs Cu	Lbs Zn	Oz Ag	Oz Au	Lbs Pb
1884-1888[1]	26,900	6,869,075		323,726	4,242	
1889	10,000	1,910,890		154,260	9,697.5	
1890	26,000	5,257,421		423,714		
1891	37,000	7,360,000				
1892	50,000	9,845,666		109,878	2,442.7	
1893	50,000	9,222,141				
1894	58,990	11,043,542		276,258	7,778.8	
1895	60,201	16,522,181		263,080	4,627.9	
1896	116,994	22,366,425				
1897	151,266	31,355,027		526,114	9,773.6	
1898	219,831	42,453,316				
1899	254,138	43,995,733		486,470	13,956.7	
1900	245,352	39,888,472		523,723	15,943	
1901	248,646	34,438,441		504,277	15,695	
1902	133,219	19,407,080		306,784	9,551	
1903	156,970	23,771,597		450,603	15,038	
1904	268,412	29,274,610		668,612	23,762	
1905	273,523	32,683,951		486,041	15,915	
1906	274,181	38,836,441		428,317	12,913	
1907	253,566	33,015,457		356,939	11,734	
1908	241,915	36,183,089		494,574	20,334	
1909	280,534	36,695,455		495,477	17,021	
1910	323,569	38,663,880		563,132	19,267	
1911	304,949	33,164,520		461,168	15,239	
1912	351,817	31,570,152		480,518	15,069	
1913	395,674	35,344,694		641,074	20,666	
1914	397,227	32,448,170		646,573	21,400	
1915	491,992	45,127,832		903,051	28,221	
1916	694,053	58,299,573		1,030,851	26,416	
1917	813,176	71,726,634		1,223,310	29,230	
1918	861,250	77,501,595		1,292,109	29,281	
1919	469,353	42,927,666		665,327	16,838	
1920	718,851	64,952,270		910,345	18,759	
1921	132,353	13,581,488		202,716	4,090	
1922	423,543	40,845,407		554,587	12,603	
1923	1,101,456	97,560,882		2,113,162	67,541	
1924	1,257,714	98,246,081		1,846,621	48,235	
1925	1,289,350	108,210,901		2,108,348	50,196	
1926	1,285,461	107,388,418		2,242,788	55,906	
1927	1,352,387	99,969,654		2,096,681	55,897	
1928	1,580,312	118,151,126		2,113,174	55,395	
1929	1,800,607	142,290,460		2,092,418	62,096	
1930	941,196	70,720,014		1,413,333	42,938	
1931	229,789	19,891,777		309,650	10,350	
1935 U.V. thru 2/18	58,546	4,679,333		66,954	2,154	
1935 P.D. from 2/19	725,020	59,817,830		867,390	27,337	
1936	1,302,974	91,514,608		1,826,875	64,531	
1937	1,433,330	85,290,903		1,907,898	65,743	

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Table 1. Continued

Year	Tons Mined	Metals Recovered				
		Lbs Cu	Lbs Zn	Oz Ag	Oz Au	Lbs Pb
1938	772,527	55,579,814		1,040,611	41,877	
1939	740,022	55,417,033		920,091	25,652	
1940	795,784	68,111,011		917,950	17,984	
1941	1,078,462	80,858,441		1,314,725	26,649	
1942	1,212,933	86,554,613		1,279, 650	24,011	
1943	882,214	68,192,842		934,927	16,362	
1944	502,247	52,774,095		547,873	8,100	
1945	377,579	39,228,810		463,540	8,475	
1946	336,197	31,485,167		414,387	8,055	
1947	346,311	31,063,468		391,993	7,573	
1948	348,048	29,833,400		436,721	11,166	
1949	409,313	33,957,890	8,005,488	485,301	9,497	
1950	351,992	15,426,569	15,157,169	272,342	6,117	
1951	299,436	19,830,228	17,915,943	399,689	7,000	
1952	155,642	10,475,722	9,613,749	249,015	4,300	
1953 End P.D.	29,164	1,938,803	2,199,620	49,058	1,258	
---- Start						
1954 Big Hole	5,004	605,319		3,604	31.5	
1955	13,447	1,371,056		9,453	77.7	
1956	14,929	1,545,434		10,843	84.0	
1957	12,872	1,644,400		14,773	333.8	
1958	16,010	2,067,960		27,724	586.7	
1959	9,824	969,108		9,627	290.7	
1960	17,010	2,299,801		10,088	101.9	
1961	18,533	2,436,505		16,187	143.2	
1962	10,477	1,770,601		8,794	113.8	
1963	15,076	2,326,437		13,414	179.1	
1964	8,203	876,828		7,974	105.1	
1965	9,577	1,216,466		9,603	152.3	
1966	5,552	543,943		4,174	54.9	
1967	5,006	528,227		3,751	50.1	
1968	5,218	565,219		5,649	68.6	
1969	9,299	1,118,820		9,950	100.8	
1970	11,062	1,392,423		12,946	155.7	
1971	7,238	758,239		8,428	110.1	
1972	6,214	615,609		6,732	69.8	
1973	1,705	173,120		1,829	19.3	
1974	3,923	376,019		4,190	48.6	
1975[1]	598	91,292		654	6.0	
Total U.V.	20,685,383	1,978,768,862		34,360,185	971,801	
Total P.D.	12,099,195	917,312,277	52,891,969	14,720,036	381,687	
Total Big Hole	206,150	25,201,534		199,793	2,877.7	
Grand Total[2]	32,990,728	2,921,291,673	52,891,969	49,279,954	1,356,366	
ABGMT[3]	33,018,255	2,928,252,040		49,604,334	1,360,614	459,100
ABGMT Total[4]	32,588,782	2,844,403,043	97,352,100	49,732,425	1,376,108	459,100

[1]Includes data from Arizona Bureau of Geology and Mineral Technology (ABGMT).

[2]Excludes data from ABGMT.

[3]Includes 1884-1888, 1975 data from ABGMT.

[4]Total from records of ABGMT.

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Table 2. Average grades of ore types, United Verde Mine

Ore Type	Level	Copper (%)	Zinc (%)	Gold (oz per ton)	Silver (oz per ton)
United Verde ore body					
Massive sulfide	700	1.58 (44)[1]	10.79 (15)	0.053 (14)	3.42 (14)
Chert, siliceous massive sulfide	700	3.45 (16)			
Black schist	700	2.58 (12)		0.005 (34)	0.75 (34)
Massive sulfide	1200	0.55 (88)	3.41 (88)		
Black schist	1200	1.02 (17)	3.21 (17)		
Massive sulfide	3000	1.80 (109)	4.90 (98)	0.020 (43)	1.56 (31)
Black schist	3000	3.38 (109)	1.53 (7)	0.006 (88)	0.91 (78)
Chert	4500	3.70 (4)	2.22 (4)	0.116 (4)	4.00 (4)
Siliceous massive sulfide	4500	3.89 (17)	10.98 (14)	0.109 (17)	3.70 (17)
Massive sulfide	4500	2.25 (62)	9.91 (55)	0.068 (60)	2.22 (56)
Black schist	4500	1.35 (21)		0.002 (9)	0.71 (9)
Haynes ore body					
Massive sulfide	3000	0.49 (37)	4.29 (28)	0.050 (36)	0.50 (36)

[1] (44), number of samples averaged

Table 3. Correlation coefficients for ore types in the United Verde massive sulfide deposit.
[A, no Zn analyses; B, no Au, Ag analyses]

Level, ore type	Correlation Coefficients					
	Cu vs Zn	Cu vs Au	Zn vs Au	Cu+Zn vs Au	Ag vs Au	Cu+Zn vs Ag+Au
All levels, massive sulfide (92)[1]	-.400	.024	.475	.528	.385	.232
All levels, siliceous massive sulfide (14)	.090	.398	.514	.610	.335	.470
All levels, massive plus siliceous massive sulfide (106)	-.302	.173	.480	.570	.434	.316
All levels plus Haynes orebody, massive sulfide (120)	-.260	-.007	.256	.260	.209	.337
700, massive sulfide (15)	-.938	-.428	.388	.357	.381	-.471
3000, massive sulfide (29)	-.643	.740	-.480	.475	.150	.221
4500 massive sulfide (48)	-.279	-.104	.484	.477	.486	.264
Haynes 3000, massive sulfide (28)	-.040	.060	-.086	-.071	.127	-.081
All levels, black schist (115)	A	.291	A	A	.426	A
All levels, quartz porphyry (15)	A	.293	A	A	.495	A
All levels, massive sulfide (137)	-.168	B	B	B	B	B
All levels, black schist (22)	-.035	B	B	B	B	B