The Nature and Possible Significance of the Batamote Copper-Bismuth-Silver Anomaly, Pima County, Arizona

U.S. GEOLOGICAL SURVEY BULLETIN 1907

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

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By DAVID L. HUSTON and PAUL K. THEOBALD

Detailed stream-sediment and heavy-mineral concentrate sampling undertaken in the Batamote Mountains, and hypotheses as to the cause of the Batamote anomaly

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DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

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UNITED STATES GOVERNMENT PRINTING OFFICE: 1990

For sale by the
Books and Open-File Reports Section
U.S. Geological Survey
Federal Center
Box 25425
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Huston, David L.
The nature and possible significance of the Batamote copper-bismuth-silver anomaly, Pima County, Arizona / by David L. Huston and Paul K. Theobald.

p. cm. — (U.S. Geological Survey bulletin ; 1907)
Includes bibliographical references.
Supt. of Docs. no.: I 19.3:1907
1. Copper ores—Arizona—Batamote Mountains Region. I. Theobald, P.K. (Paul Kellogg), 1928– . II. Title. III. Series.
QE75.B9 no. 1907
[QE390.2.C6]
557.3 s—dc20 90–2857
[553.4'3'0979177] CIP

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The Nature and Possible Significance of the Batamote Copper-Bismuth-Silver Anomaly, Pima County, Arizona

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ABSTRACT

Detailed stream-sediment and heavy-mineral-concentrate sampling and reconnaissance geologic mapping were undertaken in the Batamote Mountains of southwestern Arizona to determine the nature and distribution of a widespread copper anomaly discovered by the USGS (U.S. Geological Survey) (Barton and others, 1982). This study illustrates methodology by which the nature and distribution of such an anomaly can be determined and shows the difficulties in interpreting the information gathered.

Stream-sediment sampling yielded two broad anomalous areas that are characterized by a copper-bismuth-silver suite in the northwestern and north-central Batamote Mountains. The anomalous values are spatially associated with a series of north- to northeast-striking normal faults.

Sequential analyses suggested that anomalous copper is held predominantly in iron and manganese oxides, but a significant portion is held in a reduced form. Analysis for copper in pyrite grains from heavy-mineral concentrates indicated that coarser grained pyrite could not have contributed enough copper to produce the observed anomalies.

Analysis of the C–3 (nonmagnetic) fraction of heavy-mineral concentrates produced a similar anomaly pattern for copper, but no enhancement was realized relative to stream sediments. These analyses also yielded three other anomalous areas characterized by As-Sb±Sn±Cu±Mo, Sn-Mo, and Ag-As-Mo assemblages, respectively. The nature of these anomalies remains problematic.

The anomalies in stream sediments are best explained as the result of dispersion along normal faults; however, airborne contamination from a smelter located south of the town of Ajo (5 to 10 mi south-southwest of the study area) cannot be ruled out. The original source of metals in the normal faults could not be determined from the study.

INTRODUCTION

The maps presented in this report are part of a folio of the Ajo 1°×2° quadrangle, Arizona, prepared under the Conterminous United States Mineral Assessment Program (CUSMAP). Other publications in this folio include U.S. Geological Survey Open-File Reports 82–419 (Barton and others, 1982) and 83–734 (Theobald and Barton, 1983). Geochemical sampling was conducted as part of this program, and anomalous copper was found in stream sediments from washes draining the Batamote Mountains, 10 miles northeast of Ajo, Ariz. (Barton and others, 1982).

The purpose of this study is to define, characterize, and explain an anomaly that, as defined by this initial study, encompasses the western two-thirds of the Batamote Mountains. The following five mechanisms are considered to be possible explanations: (1) airborne contamination from a smelter located in Ajo; (2) abnormally high background copper in the volcanic rocks of the Batamote Mountains; (3) primary hydrothermal mineralization within the study area; (4) dispersion through the volcanic pile along normal faults; and (5) contamination of the volcanic rocks by copper-rich wall rocks immediately before or during volcanic eruption. For each of these working hypotheses, the anomaly should demonstrate a unique dispersion pattern and a characteristic partitioning of copper among mineral phases.

The smelter is located just south of the town of Ajo. Rose and others (1979) have summarized several instances of smelter contamination causing soil anomalies downwind of smelters; consequently, airborne

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Manuscript approved for publication May 13, 1988

dispersion from the smelter could produce the observed anomalies. Dispersion from this source would tend to be plumose in form and decrease in intensity downwind. Any copper would initially be held in fly ash as part of smelter dust but could be dispersed into other chemical phases upon weathering.

The second possible mechanism, abnormally high background values, would be characterized by a uniform distribution of anomalous values in stream sediments from a single rock unit. Additionally, the source rock unit would exhibit comparably high copper concentrations; the copper would probably be held as a trace component within silicate minerals or in accessory sulfide minerals.

Primary hydrothermal mineralization would be characterized by a dispersion pattern localized around the mineralization, and the anomalies would tend to be limited in areal extent. Given the aridity and the nature of weathering in the Batamote Mountains, primary copper minerals could be preserved in sediments.

Dispersion of copper along normal faults and nearby fractures and joints could yield broad dispersion patterns in stream sediments related spatially to the faulting. In the faults, fractures, and joints, copper could be held as oxides or sulfides; in stream sediments, the copper could be held as oxides, sulfides, or chrysocolla, or with organics.

The final mechanism considered, contamination of the volcanic rocks by wall rocks before or during volcanic eruption, would produce uniformly high values in streams draining the volcanic rocks or a zonation about the volcanic center. If the contaminants were not totally assimilated, the bulk of the volcanic rocks would not contain unusual values of copper—only xenolithic fragments would contain anomalous copper. However, if the hypothesized contaminants were totally assimilated, the dispersion would be similar to that observed for an andesite with high background values of copper.

To evaluate the five hypothesized mechanisms, the surficial distribution and dispersion of copper were determined within the Batamote Mountains. These data, in combination with lithogeochemical and geological data, were then used to infer the source of the copper anomaly discovered by Barton and others (1982).

The study, conducted between December 1982 and February 1984, involved the collection of stream-sediment, heavy-mineral-concentrate, and rock-chip samples and follow-up reconnaissance geologic mapping and resampling. The results are tabulated in Huston (1984).

LOCATION AND PHYSIOGRAPHY

The study was conducted in the Batamote Mountains, within the Basin and Range province in southwestern Arizona, 5–10 air miles northeast of Ajo in Pima County. Ajo is the site of Phelps Dodge's New Cornelia porphyry copper deposit and smelter. Figure 1 shows the location of the study area in relation to Ajo, Phoenix, and Tucson.

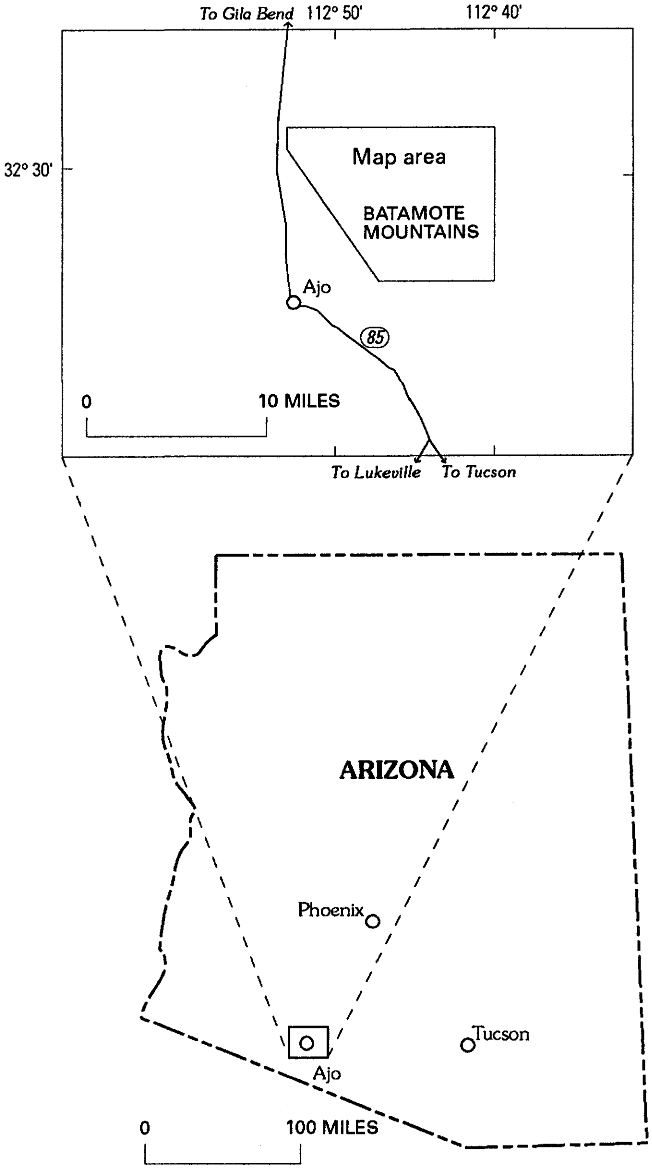


Figure 1. Location of Batamote study area, Arizona.

The west-northwest-trending Batamote Mountains have a length of twelve miles and a width of as much as 5 miles. Maximum elevation is 3,202 ft with relief of 1,700 ft. The mountains are relatively low plateaus surrounding a central peak. The youthful drainages are characterized by narrow canyons having moderate to steep gradients (Gilluly, 1937). The streams are all ephemeral.

LOCAL GEOLOGY

The regional geology of the study area was described by Gilluly (1935, 1937, 1942, and 1946) and summarized by Huston (1984). Papers relating to stream-sediment geochemistry and geophysics of the study area include those by Barton and others (1982, compilation of stream-sediment and heavy-mineral-concentrate analyses), Theobald and Barton (1983, statistical treatment of geochemical data), and Klein (1982, residual aeromagnetic map).

The study area was mapped at a reconnaissance scale (1:63,360) using aerial photographs, and the geology was subsequently field checked and compared against other compilations. Map A is a generalized geologic map of the area. Two distinct bedrock units were recognized, the Tertiary Childs Latite and the Batamote Andesite. The Batamote Andesite has been divided into three subunits—extrusive, intrusive, and vent facies—following Gilluly's 1946 terminology. Two distinctive alluvial units are present.

Lithology and stratigraphy

Childs Latite

The Miocene Childs Latite (Tcl on map A), with an age between 17 and 20 m.y. (May and others, 1981), occurs predominantly along the eastern edge of the study area. The unit consists predominantly of flows having excellent flow banding and minor breccia, and dikes. Typically, the latite is holocrystalline and porphyritic-cryptocrystalline to microcrystalline, with very fine to coarse-grained anhedral phenocrysts in a felted groundmass. The phenocrysts are dominated by andesine and (or) labradorite and contain lesser amounts of orthoclase, magnetite, and augite. The groundmass consists of plagioclase, augite, and magnetite.

Batamote Andesite

The extrusive facies of the Batamote Andesite (Tba) crops out over most of the Batamote Mountains and dips away from a central plug located near the range's high point, which is interpreted to be the volcanic vent. This unit occurs predominantly as flows with thicknesses as much as 60 ft. The flows show a strong textural zonation, typically grading from a basal gray, fissile rock of aphanitic texture, through an intermediate black, massive, aphanitic section, and finally into a black, scoriaceous cap. Mineralogically, the flows are dominated by andesine and (or) labradorite and contain accessory olivine and magnetite and minor hypersthene and augite.

The vent facies of the Batamote Andesite (Tbv) consists of 4- to 36-in blocks of red to maroon volcanic breccia in an aphanitic to coarse-grained matrix. The unit is peripheral to the intrusive facies in the central part of the study area, just southwest of the high point of the Batamote Mountains.

The intrusive facies of the Batamote Andesite (Tbi) can be split into two distinct subunits, a fine-grained equigranular diorite (or gabbro?) and a dense, massive porphyritic to aphanitic basaltic andesite. The diorite is dominated by andesine and contains accessory olivine and magnetite and minor intergranular augite and hypersthene. The andesite is composed predominantly of andesine to labradorite and accessory olivine and lesser hypersthene, magnetite, and augite.

The Batamote Andesite is of Miocene age (15.52±0.54 m.y., Shafiqullah and others, 1980). It unconformably overlies the Childs Latite.

Alluvium

Both units of alluvium postdate the Batamote Andesite. The older unit (QTa) consists of unconsolidated gravels and forms low sinuous ridges in the north and a dissected pediment in the south. The younger unit (Qa) is a poorly sorted, active Quaternary alluvium filling intermountain valleys.

Alteration

The Batamote Andesite is notable for its lack of significant alteration. The only secondary minerals observed in the unit are amygdaloidal zeolites and joint- and fracture-filling chalcedony. A "limonite" multispectral-imaging anomaly occurs around the Batamote plug (Gary Raines, USGS, personal communication, 1984), but no mineralization was observed in the plug. An extensive zone of argillic alteration was observed in the Childs Latite exposed in an embayment in the Batamote Andesite in the northeastern part of the study area.

Structure

Structural deformation in the study area is limited to normal faults and very minor warping. The northwestern part of the Batamote Mountains is cut by a series of north- to northeast-striking normal faults. Folding is limited to relatively minor warps in the Batamote Andesite (Gilluly, 1946) and an anticline in the Childs Latite.

LITHOGEOCHEMISTRY

A total of 58 rock-chip samples collected within the study area were pulverized and analyzed for 31 elements using semiquantitative emission spectrography (Grimes and Marranzino, 1968). The results of these analyses are presented in Huston (1984). The sample locations are plotted on map B. Of these samples, 41 were collected from the extrusive facies of the Batamote Andesite, five from the Childs Latite, and six from other rock types.

A histogram (fig. 2) shows the distribution of copper in the extrusive facies of the Batamote Andesite. Reported copper values have a restricted range, which is characterized by one mode at 30 ppm (parts per million), indicating that the Batamote Andesite has a relatively uniform distribution of copper. Because the average abundance of copper in andesite is 55 ppm (Zemann and Wedepohl, 1972), the Batamote Andesite is somewhat depleted in copper relative to other rocks of similar composition.

STREAM-SEDIMENT GEOCHEMISTRY

A total of 101 minus-30-mesh stream-sediment samples from 89 sample sites in and around the Batamote Mountains were collected (map C). Minus-30-mesh stream sediment was collected to minimize the effect of eolian contamination and dilution (compare with Theobald and Allcott, 1973). A pilot study of seven samples showed that copper anomalies could be determined as consistently from the minus-30-mesh fraction as from finer fractions.

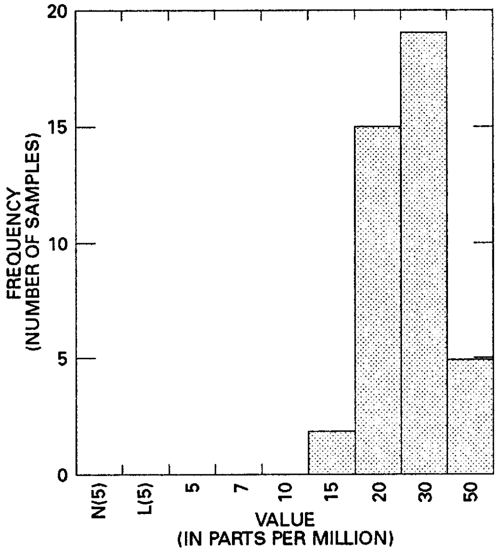


Figure 2. Histogram showing the distribution of copper in the Batamote Andesite. N, not detected at lower limit of determination, given in parenthesis; L, detected but less than lower limit of determination.

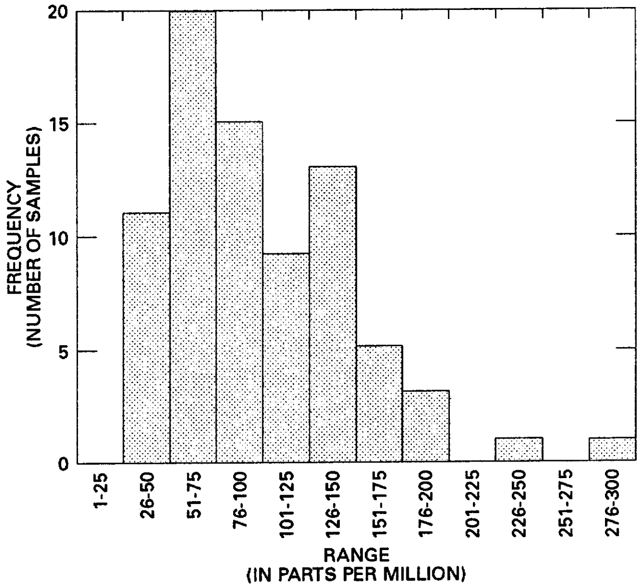


Figure 3. Histogram showing the distribution of copper (extracted using hot nitric acid and analyzed by atomic absorption spectrophotometry) in minus-30-mesh stream sediments.

Results of Total or Near-Total Analyses

The samples from each site were pulverized and analyzed for 31 elements using a semiquantitative emission spectrography method (Grimes and Marranzino, 1968) modified to lower the detection limits for Ag, As, Au, Be, Bi, Cd, Cu, Pb, Sb, Sn, W, and Zn by the use of a damped-pendulum filter to increase sensitivity for volatile elements (E.F. Cooley, USGS, personal commun., 1983). All analytical data are tabulated in Huston (1984).

Copper

The samples were also analyzed by atomic absorption spectrophotometry as described above. The results for copper using this method were similar to the results obtained by emission spectrography (the correlation coefficient was 0.8185). Figure 3 and map D show the frequency and areal distributions of copper in stream sediments using this method.

The copper values range from 30 to 280 ppm, with possibly two modes (at 75 and 150 ppm) shown on the histogram (fig. 3). If two modes are assumed, a threshold of 100 ppm is indicated. Using this threshold, two anomalous areas, separated by a trough of lower values, occur in the northwest and north-central parts of the study area (areas 1 and 2 on map D). Area 1 has a strong spatial association with the north-striking normal faults described earlier. Area 2 has no obvious lithologic or structural control.

Other Elements

Of the 31 elements determined using emission spectrography, only bismuth and silver have a discernible relationship to copper. For three elements (arsenic, antimony and tin), detection limits were too low to give unqualified values. Figures 4 and 5 show the frequency and maps E and F show the areal distributions of bismuth and silver, respectively. Unfortunately, the values determined are at or near lower detection limits for both elements.

Both bismuth and silver mimic the anomaly pattern observed for copper. High silver values (greater than or equal to "L(0.1)") have a wider distribution than copper values, yet they occur in similar areas. Bismuth correlates well with copper, even to the extent of showing a trough of low values between the two anomalies.

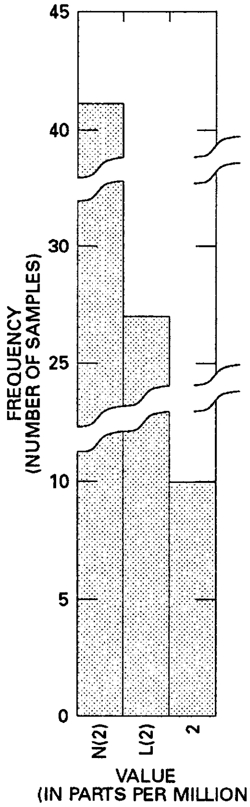


Figure 4. Histogram showing the distribution of bismuth (analyzed using semiquantitative emission spectroscopy) in minus-30-mesh stream sediment. N, not detected at lower limit of determination, given in parenthesis; L, detected but less than lower limit of determination.

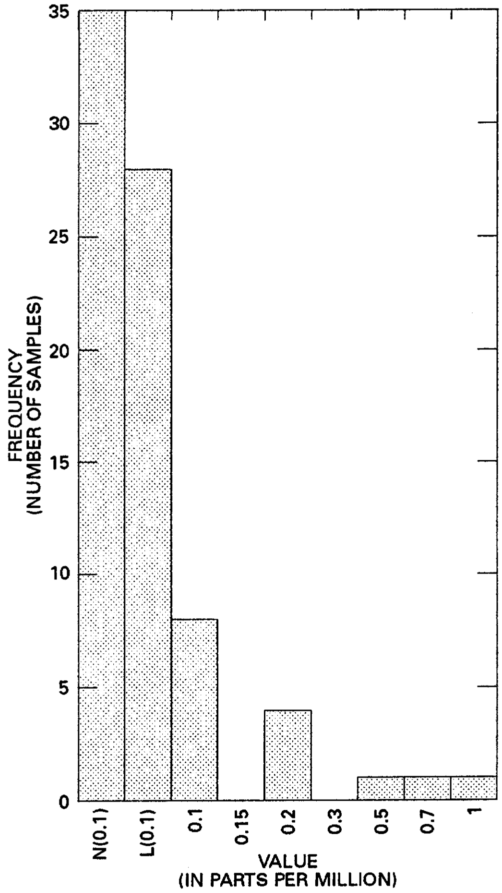


Figure 5. Histogram showing the distribution of silver (analyzed using semiquantitative emission spectroscopy) in minus-30-mesh stream sediment. N, not detected at lower limit of determination, given in parenthesis; L, detected but less than lower limit of determination.

For intermediate igneous rocks, silver has an average abundance of 0.07 ppm (Wedepohl, 1969), whereas bismuth values range from 0.1 ppm in felsic rocks to 0.15 ppm in mafic rocks (Levinson, 1980). The implied threshold for silver lies near the average abundance for intermediate volcanic rocks, whereas the threshold for bismuth ("L(2)" ppm) is an order of magnitude higher than the abundance expected for intermediate volcanic rocks. The anomaly is best characterized by copper-bismuth-silver, in that order.

Results From Sequential Extraction Methods

To determine the mineralogic distribution of copper within the stream sediments, two sequential extractions were performed. The first involved three steps and was performed in part or in total on one sample from each site. The second involved five steps and was performed on ten samples; of these, four were considered anomalous, three were considered borderline anomalous, and three were considered background.

First Sequential Analysis

In the first sequential extraction, three steps were used, as follows: (1) hot oxalic acid to remove the "oxide" fraction (T.T. Chao, USGS, personal communication, 1983); (2) potassium perchlorate and cold hydrochloric acid to remove the "reduced" (sulfide) fraction (Olade and Fletcher, 1974); and (3) aqua regia and hydrofluoric acid (Filipek and Owen, 1978) to attack residual minerals. A sample from each site was analyzed using steps 1 and 2, and 20 of these samples were also analyzed using step 3. The extraction techniques for all chemical analyses used in this study are described in Huston (1984).

The results for copper from the oxalic acid leach were normalized to iron to minimize the effect of large variations in the amount of oxide coatings in the samples. Figure 6 shows the frequency and map G shows areal distributions of copper from this step. The oxalic acid extraction is characterized by a unimodal distribution with an upper shoulder. Assuming the shoulder to contain the anomalous values, the threshold was set at 0.01. With this threshold, the same areas were found to be anomalous as with the nitric acid extraction; however, area 2 was reduced in extent.

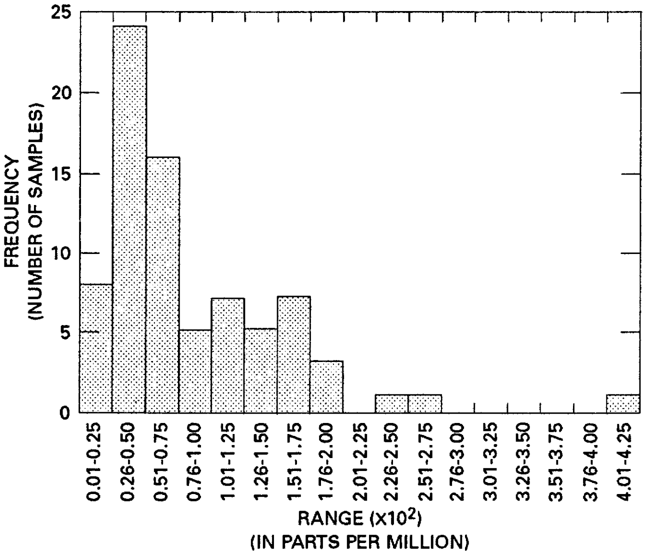


Figure 6. Histogram showing the distribution of copper normalized to iron (extracted using hot oxalic acid) in minus-30-mesh stream sediment.

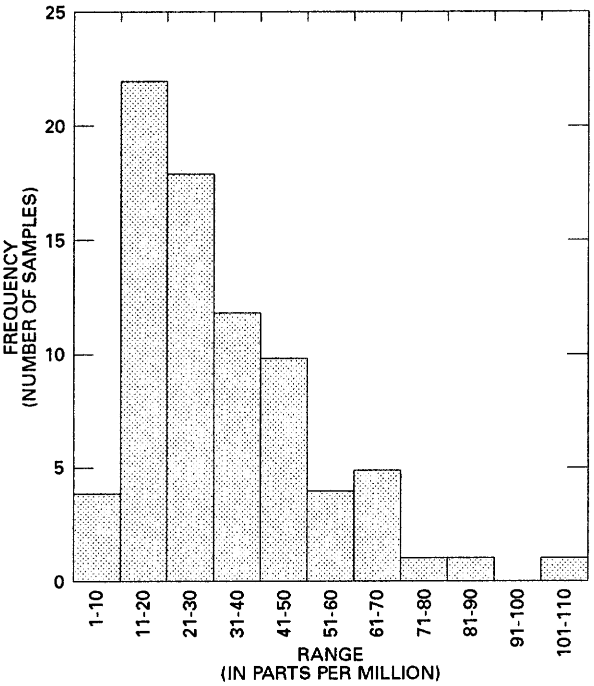


Figure 7. Histogram showing the distribution of copper (extracted sequentially using potassium perchlorate and hydrochloric acid after oxalic acid) in minus-30-mesh stream sediment.

Figure 7 shows the frequency and map H shows the areal distributions of copper extracted in step 2. In general, this second extraction, which involves potassium perchlorate and cold hydrochloric acid, contains less copper than the oxalic acid extraction. The frequency distribution has the appearance of a log-normal distribution, which is distinct from the other observed distributions. If 40 ppm is chosen as the threshold, the northwestern anomaly remains relatively unchanged, but the north-central anomaly is more spread out and has no distinct highs. Differences in frequency and areal distributions suggest that additional or different processes controlled the distribution of copper held in sulfides or organics (step 2) relative to processes that controlled the distribution of copper in iron oxides (step 1).

Step 3 indicates that copper in the residual fraction (silicates) has a concentration of about 15 ppm copper with no correlation to the distributions found in the other extractions. Copper extracted in this step probably reflects the lithogeochemical background.

Second Sequential Analysis

The second sequential extraction involved five steps to remove the following mineralogic fractions: (1) carbonate and exchangeable; (2) easily reducible; (3) moderately reducible; (4) sulfide; and (5) crystalline (silicate). Although the steps attack principally the mineralogic fractions described, they are not perfectly selective; therefore, the values determined cannot be taken as a strict description of the behavior of these elements according to mineralogic fraction. The method used is modified after Filipek and Owen (1978) and Chao and Zhou (1983).

Each of the ten selected minus-30-mesh stream sediments was separated into three parts using bromoform (specific gravity of 2.9) before pulverization, as follows: the portion that sinks (the "heavies"), the portion that remains suspended (the "slimes"), and the portion that floats (the "lights"). The heavies contain minerals with a specific gravity of 2.9 or greater—typically amphiboles, pyroxenes, olivine, magnetite, sulfides, and other heavy minerals. The slimes contain minerals that have specific gravities of about 2.9 and flocculant minerals such as clays. The lights contain minerals with specific gravities less than 2.9 such as feldspars, calcite, and quartz.

All three separates and a bulk sample for each stream sediment were analyzed for copper, iron, and manganese. For comparison, a sample with about 300 ppm copper held in chrysocolla was also prepared using quartz sand and chrysocolla. Table 1 gives the results for copper, iron, and manganese, and figure 8 graphically depicts the concentrations of copper. The following observations are pertinent: (1) Chrysocolla does not appear to be the mineral contributing a significant amount of copper to the samples. (2) Because the lights comprise the bulk of the stream sediments (always greater than 87 percent by weight), the bulk analyses reflect those of lights. (3) The heavies have the highest concentrations for all elements determined. (4) The concentrations of both iron and manganese vary independently from those of copper. (5) Copper in the crystalline fraction varies little between background and anomalous values, indicating that it is probably a regional background. In background samples, this fraction dominates copper values. (6) The carbonate and exchangeable fraction contribute relatively little to total copper, but values in anomalous samples are enriched relative to background samples. Relatively speaking, the values from this fraction are enhanced to a greater degree in the lights as opposed to the heavies and slimes. (7) The values in the easily reducible fraction are relatively constant in comparing heavies, slimes, and lights, but the anomalous stream sediments (as a group) are enriched over background samples. This suggests that copper in this fraction is probably held as coatings on grains. (8) The ratio of cold extractable copper (the sum of the carbonate and exchangeable, and easily reducible, fractions) to total copper for bulk stream sediments is significantly higher in anomalous samples than in background samples. (9) The sulfide fraction contributes most of the copper in the heavies and slimes of anomalous and borderline samples. (10) The moderately reducible fraction contains quantitatively less but proportionately more copper in the lights than the heavies or slimes. A more detailed discussion may be found in Huston (1984).

In summary, sulfides or another phase extracted in the same step are the predominant sources of copper in the heavies and slimes, whereas the oxides (that is, easily and moderately reducible fractions) are the predominant source in the lights.

Follow-Up Work

To check the distribution of copper in the anomalous drainages, samples were collected upstream from sites AJ003S and AJ039S (sites 3 and 39, respectively, on map C). The samples were analyzed using semiquantitative emission spectrography, the nitric acid leach, the oxalic acid leach, and the potassium perchlorate-hydrochloric acid leach. All analyses except emission spectrography illustrate that anomalous concentrations of copper do not change significantly up drainage. Figures 9 and 10 depict this point using the results of the oxalic acid leach.

The lack of significant variation upstream from anomalous samples (1) implies that the input of anomalous copper occurs throughout the drainage area of anomalous sample sites and (2) argues against input from a single structure or localized source. Instead, the copper apparently came from a source that does not change in intensity over a wide area.

HEAVY-MINERAL-CONCENTRATE GEOCHEMISTRY

At each sample site (except follow-up sites), a heavy-mineral-concentrate sample was collected and later panned. Four sites were resampled during follow-up to confirm anomalies. For consistency with the stream-sediment data, these samples were sieved through a 30-mesh-screen and the minus-30-mesh material was separated into a light and a heavy fraction using bromoform. The heavies were saved and passed through a Frantz Isodynamic Magnetic Separator (front slope, 5°; side slope, 10°). Three fractions of varying magnetic susceptibility were separated by varying the current and were labeled "C–1" (less than 0.2 amps), "C–2" (0.2–0.6 amps), and "C–3" (greater than 0.6 amps). The relatively nonmagnetic C-3 fraction was split, and one split was analyzed using semiquantitative emission spectrography. The other split was used to determine the mineralogy by binocular microscope. The analytical results are presented in Huston (1984).

Table 1. Analytical results of the second sequential extraction on stream sediments, Batamote Mountains, Ariz.

[Values in parts per million; except Cu/Cu, given as ratio, Cu, copper; Fe, iron; Mn, manganese; cxCu/Cu, cold extractable copper/total copper ratio; N, not detected at lower limit of determination, given in parentheses; L, detected but below the lower limit of determination]

		Mineralogic fraction															
		Carbonate/Exchangeable			Easily reducible			Moderately reducible			Sulfide/Organic			Crystalline			
Sample	Density separate	Cu	Fe	Mn	Cu	Fe	Mn	Cu	Fe	Mn	Cu	Fe	Mn	Cu	Fe	Mn	cxCu/Cu
AJ012S	Bulk	6	13	40	15	61	40	17	400	50	9	320	15	34	18,000	140	0.259
	Heavies	23	52	70	23	260	50	64	1,900	50	240	750	25	59	270,000	2,650	0.112
	Slimes	9	12	65	28	66	50	27	600	65	39	740	30	66	41,000	340	0.219
	Lights	6	20	40	13	61	35	14	400	40	1	230	10	22	13,000	65	0.339
AJ015S	Bulk	4	11	40	14	62	40	17	400	45	10	220	10	46	26,000	220	0.198
	Heavies	12	30	60	19	200	65	51	1,600	100	180	500	25	105	290,000	2,450	0.084
	Slimes	6	12	50	19	65	40	22	600	75	15	280	20	58	40,000	440	0.208
	Lights	4	15	35	13	61	35	12	200	35	4	170	10	26	18,000	100	0.288
AJ019S	Bulk	24	13	55	49	113	35	38	400	25	52	430	10	54	15,000	70	0.336
	Heavies	57	56	75	46	270	25	120	1,400	60	460	1,350	25	115	105,000	1,950	0.129
	Slimes	36	16	90	52	121	30	49	700	40	200	1,100	25	82	31,000	280	0.210
	Lights	25	14	60	45	129	30	35	400	15	32	580	10	32	12,000	45	0.414
AJ038S	Bulk	18	11	40	31	142	45	29	400	20	33	420	15	44	17,000	95	0.316
	Heavies	65	52	65	46	300	30	180	2,800	80	520	1,500	20	105	65,000	1,200	0.121
	Slimes	33	19	50	50	160	125	65	1,400	55	240	1,100	30	77	51,000	580	0.178
	Lights	18	18	45	31	139	40	27	500	20	9	290	10	36	10,000	40	0.405
AJ039S	Bulk	26	13	50	41	114	40	39	500	20	38	450	10	46	18,000	90	0.353
	Heavies	56	59	60	46	305	30	125	3,000	80	480	1,450	20	95	95,000	1,950	0.127
	Slimes	46	22	70	67	200	30	75	1,100	45	360	1,100	25	115	45,000	580	0.170
	Lights	25	20	50	40	118	35	30	300	15	14	310	10	40	13,000	60	0.436

Table 1. Analytical results of the second sequential extraction on stream sediments, Batamote Mountains, Ariz.—Continued

		Mineralogic fraction															
Sample	Density separate	Carbonate/Exchangeable			Easily reducible			Moderately reducible			Sulfide/Organic			Crystalline			cxCu/Cu
		Cu	Fe	Mn	Cu	Fe	Mn	Cu	Fe	Mn	Cu	Fe	Mn	Cu	Fe	Mn	
AJ040S	Bulk	15	14	40	27	62	25	31	400	40	21	340	15	44	17,000	85	0.304
	Heavies	41	54	65	31	290	35	110	2,000	95	460	1,250	20	90	65,000	1,250	0.098
	Slimes	27	16	75	53	89	50	70	1,000	70	250	980	30	125	50,000	560	0.152
	Lights	14	22	40	23	60	30	25	400	30	5	250	10	36	13,000	85	0.359
AJ049S	Bulk	5	13	45	12	74	50	17	800	55	8	420	15	43	26,000	200	0.200
	Heavies	9	120	150	15	350	90	42	3,800	115	80	730	30	100	85,000	1,500	0.098
	Slimes	5	12	50	19	62	40	35	900	135	63	1,050	35	64	44,000	150	0.129
	Lights	5	17	40	11	49	40	14	400	50	4	390	15	30	21,000	130	0.250
AJ069S	Bulk	2	15	45	8	98	45	10	600	30	6	360	15	28	23,000	120	0.185
	Heavies	5	160	170	8	335	60	24	3,800	90	40	450	15	60	115,000	2,400	0.095
	Slimes	2	13	65	9	76	40	22	800	135	41	420	25	75	55,000	760	0.074
	Lights	2	20	45	7	68	35	8	200	20	4	230	10	22	15,000	70	0.209
AJ094S	Bulk	2	15	45	4	91	45	7	700	40	7	410	20	26	19,000	90	0.310
	Heavies	6	130	130	7	340	55	27	3,000	140	35	420	20	52	75,000	960	0.102
	Slimes	2	11	55	9	73	40	14	1,100	19	19	720	40	48	60,000	680	0.120
	Lights	2	21	45	4	82	40	6	500	30	2	370	15	22	17,000	70	0.167
AJ103S	Bulk	2	23	45	5	110	60	8	1,500	85	3	450	20	29	28,000	170	0.212
	Heavies	7	240	180	9	485	60	21	5,800	90	36	610	30	70	330,000	3,050	0.112
	Slimes	2	10	60	12	68	50	17	2,000	135	18	890	40	52	43,000	270	0.139
	Lights	2	36	50	5	93	50	6	1,300	75	3	400	20	17	17,000	60	0.212
Chrysocolla Standard		230	14	5	23	17	L(5)	20	N(100)	N(5)	7	80	N(5)	5	L(1,000)	L(5)	0.888

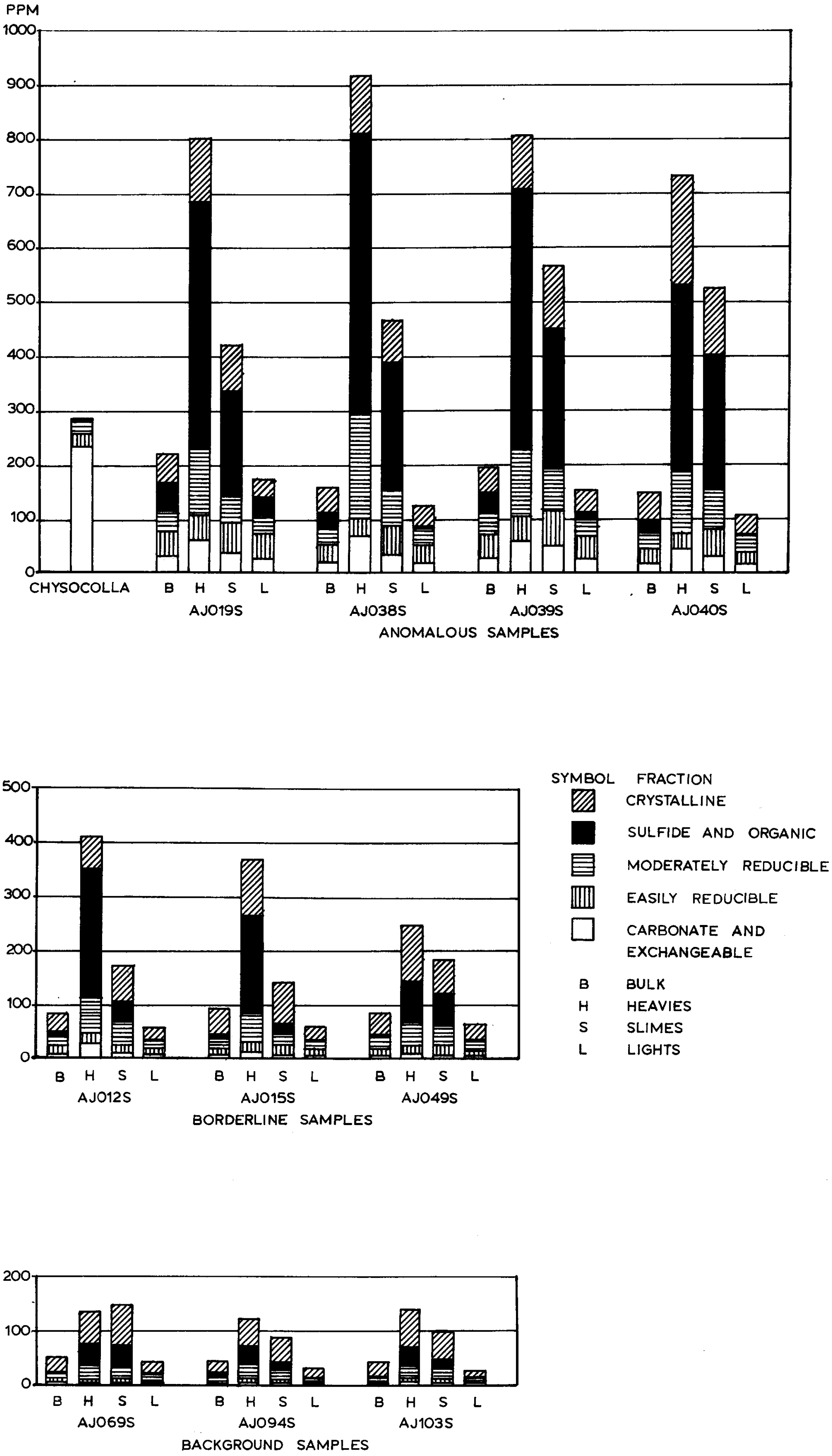
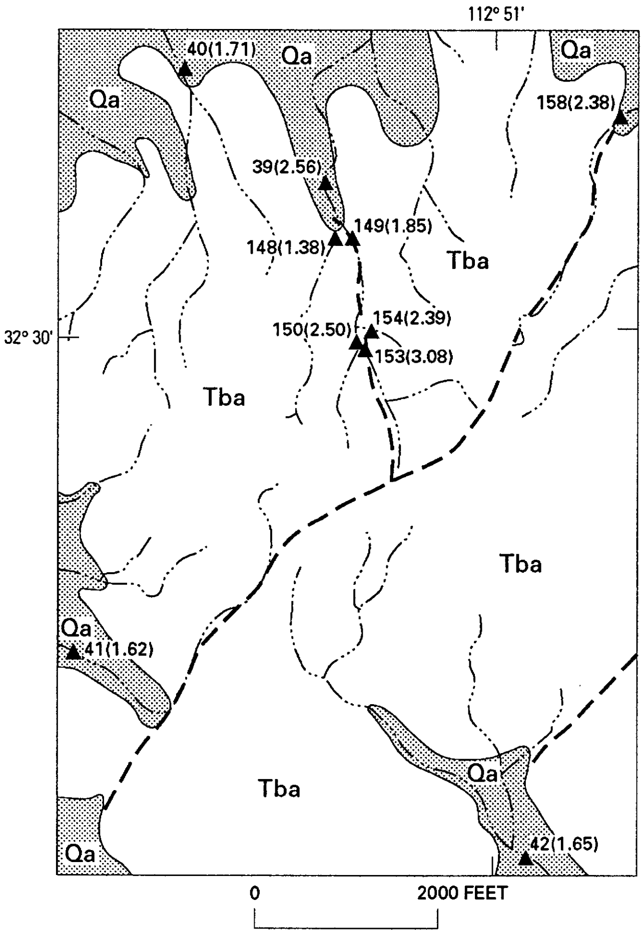


Figure 8. Distribution of copper among mineralogic and density fractions of selected stream sediments, Batamote Mountains, Ariz.



EXPLANATION

Qa **Quaternary alluvium**

Tba **Tertiary Batamote Andesite**

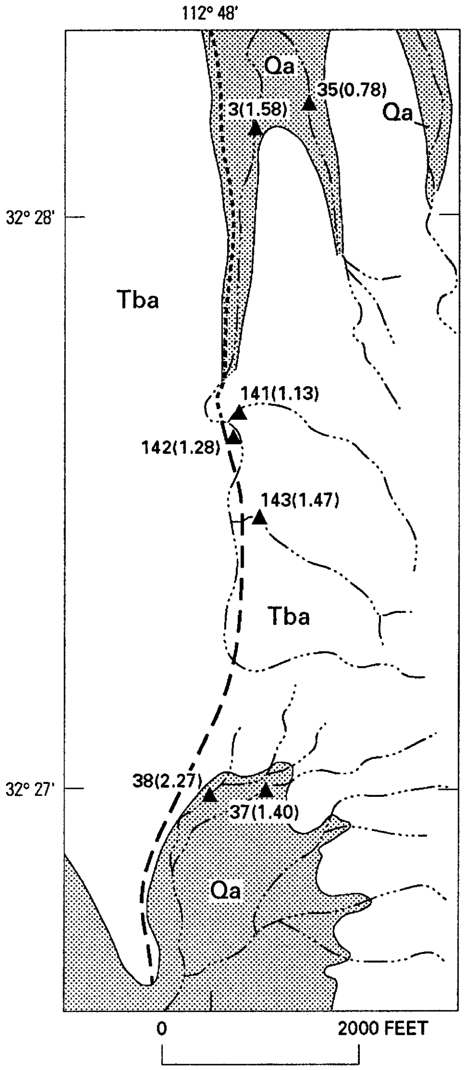
—··—··— **Stream**

——— **Contact**

——— **Fault**—Dashed were approximately located

▲42(1.65) **Sample site and number**—Concentration ratio, in ppm Cu per 100 ppm Fe, given in parenthesis

Figure 9. Distribution of copper normalized to iron (extracted using oxalic acid) in minus-30-mesh stream-sediment samples upstream from anomalous sample AJ039S (site 39 on map C; from reconnaissance data of Barton and others, 1982).



EXPLANATION

Qa **Quaternary alluvium**

Tba **Tertiary Batamote Andesite**

—··—··— **Stream**

——— **Contact**

——— **Fault**—Dashed were approximately located; dotted were concealed

▲3(1.58) **Sample site and number**—Concentration ratio, in ppm Cu per 100 ppm Fe, given in parenthesis

Figure 10. Distribution of copper normalized to iron (extracted using oxalic acid) in minus-30-mesh stream-sediment samples upstream from anomalous sample AJ003S (site 3 on map C; from reconnaissance data of Barton and others, 1982).

The replicate samples confirmed the anomalies; however, the replicate values fluctuated significantly from the original samples. This nonreproducibility is due to variability in the hydraulics of the sample location, the small amount of sample analyzed (5 mg), and the small amount of C–3 sample available after preparation (0.04–1.29 g).

Copper

Both the frequency and areal distributions of copper in the C–3 fraction of heavy-mineral concentrates (see fig. 11 and map I, respectively) differ from those determined from bulk stream sediments. The correlation coefficient between these two sample media is only 0.4395 for copper. The frequency distribution for this medium appears to be unimodal, with the mode occurring at 150 ppm.

If a threshold of 200 ppm is used, the anomalous values of copper occur without any systematic order. However, if a cutoff of 150 ppm is used (this includes 63 percent of the samples), the northwestern two-thirds of the study area would be anomalous. This area is consistent with, but much larger than, the anomalous areas observed with stream sediments.

To evaluate a possible source of copper in the C–3 fraction, pyrite grains from seven samples were analyzed using a microprobe. Two samples were considered anomalous; two were considered borderline anomalous; and three were considered background on the basis of stream-sediment results. Two pyrite grains from anomalous samples contained high values of copper (as much as 3,400 ppm), but grains from the borderline anomalous samples did not contain significantly more copper than those in background samples (Huston, 1984). Pyrite made up at most 1 percent of the C–3 fraction; therefore, even the highest concentration of copper in relatively coarse pyrite grains could not account for the observed values in this medium, let alone in the stream sediments.

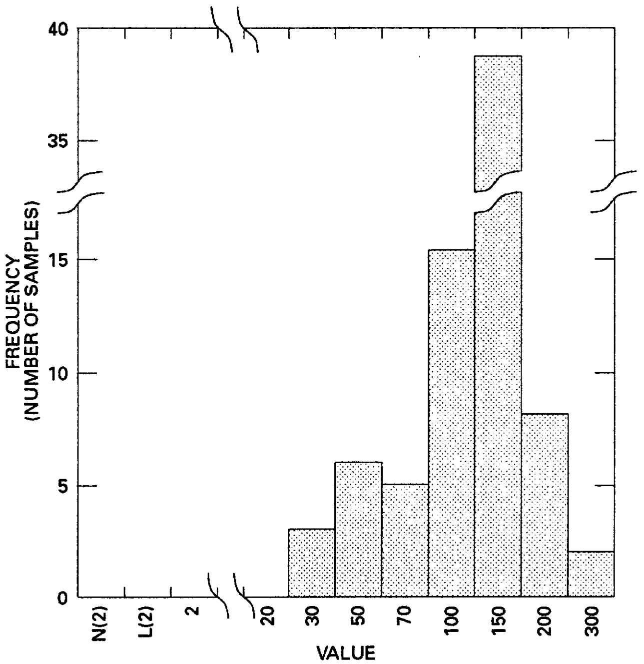


Figure 11. Histogram showing the distribution of copper in the nonmagnetic C–3 fraction of heavy-mineral concentrates. N, not detected at lower limit of determination, given in parenthesis; L, detected but below lower limit of determination.

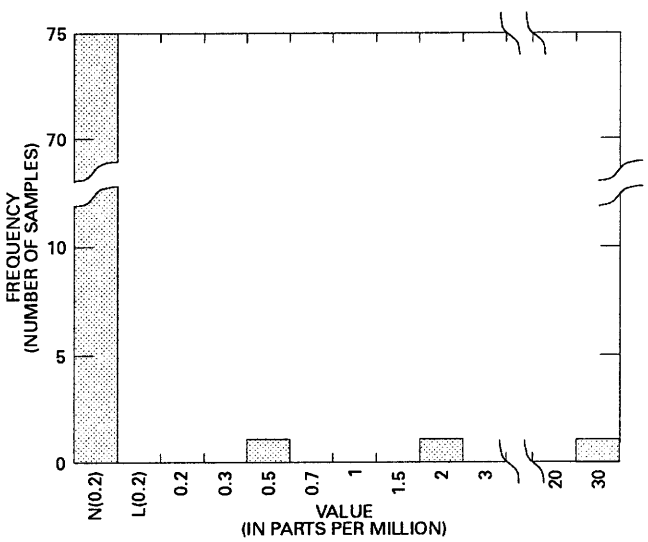


Figure 12. Histogram showing the distribution of silver in the nonmagnetic C–3 fraction of heavy-mineral concentrates. N, not detected at lower limit of determination, given in parenthesis; L, detected but below lower limit of determination.

The C–3 fraction does not enhance the values observed in stream sediments, because the highest values reported in both media are about 300 ppm. Therefore, the minerals in the C–3 fraction cannot be the sole source of the anomalies observed in stream sediments. The distribution observed is consistent with known stream-sediment anomalies, but it does not enhance them in any way.

Other Elements

A totally unexpected result of this study was the discovery of significant anomalous values for other interesting elements besides copper in the C–3 fraction of heavy-mineral concentrates. Map J shows the distribution of anomalous values (upper 10 to 15 percent of reported values) of silver, arsenic, barium, copper, molybdenum, lead, antimony, tin, and zinc. Figures 12 through 19 show frequency distributions of these elements (except copper).

On the basis of the clustering of anomalous values of elements with similar geochemical associations, three anomalies were considered most significant.

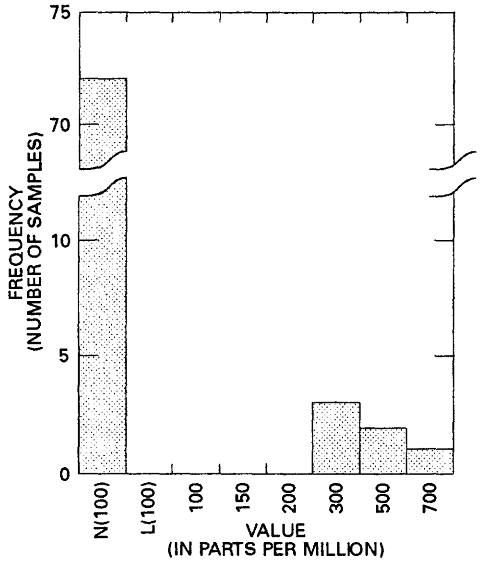


Figure 13. Histogram showing the distribution of arsenic in the nonmagnetic C-3 fraction of heavy-mineral concentrates. N, not detected at lower limit of determination, given in parenthesis; L, detected but below lower limit of determination.

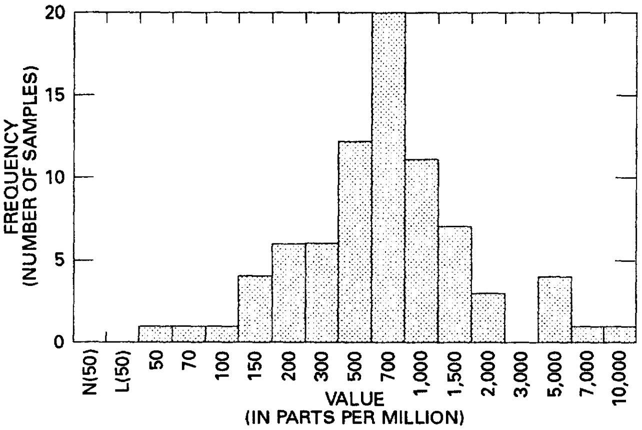


Figure 14. Histogram showing the distribution of barium in the nonmagnetic C-3 fraction of heavy-mineral concentrates. N, not detected at lower limit of determination, given in parenthesis; L, detected but below lower limit of determination.

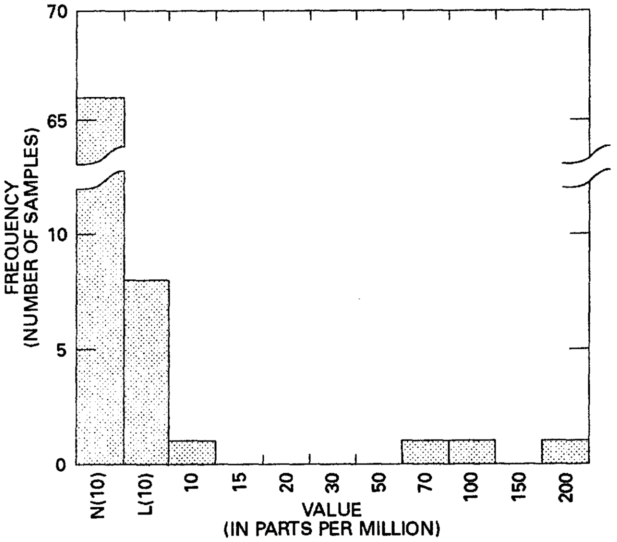


Figure 15. Histogram showing the distribution of molybdenum in the nonmagnetic C–3 fraction of heavy-mineral concentrates. N, not detected at lower limit of determination, given in parenthesis; L, detected but below lower limit of determination.

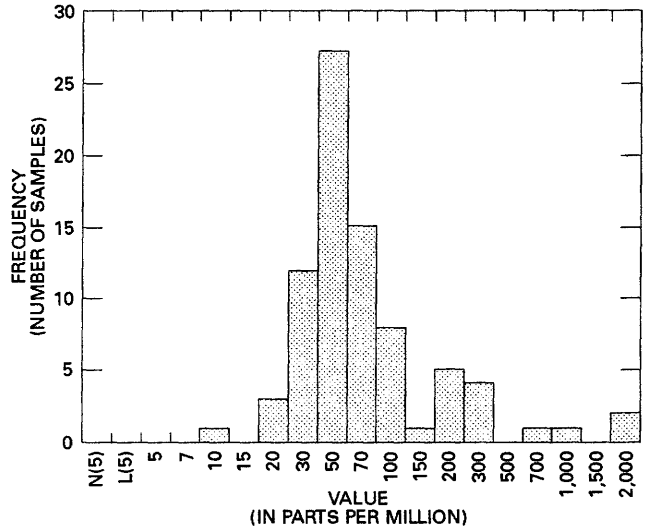


Figure 16. Histogram showing the distribution of lead in the nonmagnetic C–3 fraction of heavy-mineral concentrates. N, not detected at lower limit of determination, given in parenthesis; L, detected but below lower limit of determination.

Anomaly 1, located in the northeast part of the study area, consists of a tight grouping of three samples having anomalous values of molybdenum and tin. The samples were taken from washes that drain the Childs Latite in the area where alteration was observed. The Childs Latite has produced anomalous tin values in other parts of the Ajo 1° by 2° quadrangle (Barton and others, 1982).

Anomaly 2, defined by a clustering of four samples showing high values of the volatile elements arsenic and antimony and lesser copper, molybdenum and tin, occurs in the north-central part of the study area. Resampling of two sites confirmed the anomaly. A contiguous sample (AJO56C) also contained grains of chalcopyrite and covellite, although only 70 ppm copper was reported in the analysis. No alteration or mineralization to explain the anomaly was observed during traverses along the drainages.

Anomaly 3, located towards the southeast, consists of a group of six samples showing high values of silver, molybdenum, and arsenic. This anomaly is the most obscure because no mineralization was seen on the ground or during visual examination of the sample (only one sample contained arsenopyrite).

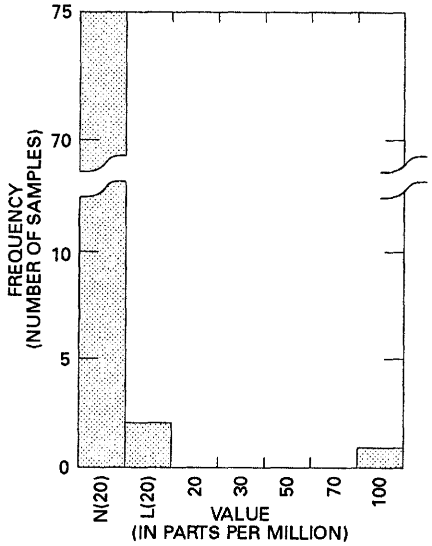


Figure 17. Histogram showing the distribution of antimony in the nonmagnetic C-3 fraction of heavy-mineral concentrates. N, not detected at lower limit of determination, given in parenthesis; L, detected but below lower limit of determination.

Mineralogy

The nonpulverized split of the C–3 fraction was examined under the binocular microscope to determine the minerals present. This fraction contained sphene, zircon, and apatite as the dominant minerals. Pyrite, chalcopyrite, covellite, arsenopyrite, galena, barite, cerussite, wulfenite(?), cassiterite, and copper carbonates occurred in one or more samples. Other materials observed in the samples include lead shot, caliche fragments, rock fragments, and pyroxene. Maps K and L show the distribution of ore-related minerals.

From these data, two generalizations can be made. First, pyrite occurs throughout the study area. Its widespread occurrence and limited concentration imply that pyrite is a minor accessory mineral in the Batamote Andesite. Second, high values of lead, bismuth, antimony, and tin should not be trusted. In three samples, lead shot was observed, raising the possibility of contamination in other samples. Bismuth, antimony, and tin are common alloys in shot. Solitary high lead values should be regarded with suspicion.

Other minerals are reflected by elemental analysis to a greater or lesser degree. Observed arsenic-bearing minerals include arsenopyrite; tin-bearing minerals include cassiterite; lead-bearing minerals include galena, metallic lead (shot), cerussite, and wulfenite (also molybdenum bearing); and copper-bearing minerals include chalcopyrite, copper carbonates, and covellite.

Anomaly 1 is caused by the presence of cassiterite. Anomaly 2 is caused by the presence of arsenopyrite, chalcopyrite, malachite, and covellite. In Anomaly 3, only one sample was observed to contain arsenopyrite. Other scattered mineral occurrences were observed in the C–3 fraction of heavy-mineral concentrates from samples collected throughout the study area.

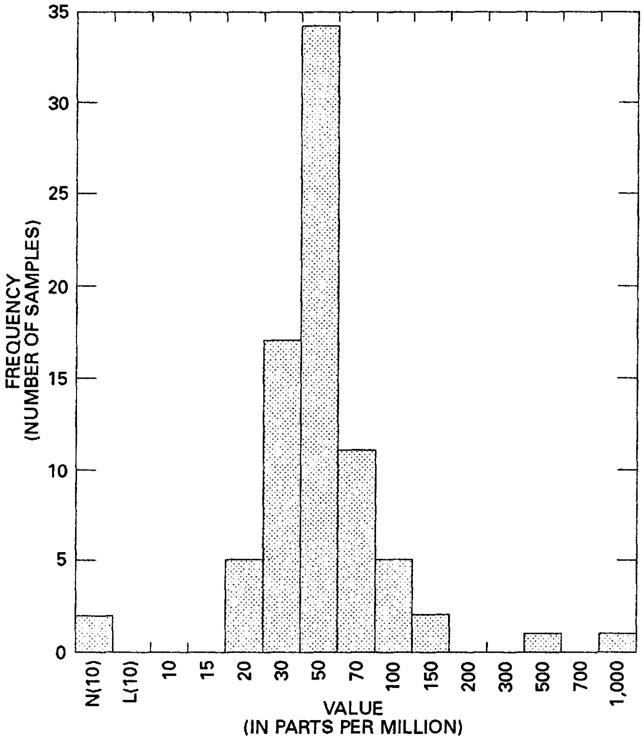


Figure 18. Histogram showing the distribution of tin in the nonmagnetic C–3 fraction of heavy-mineral concentrates. N, not detected at lower limit of determination, given in parenthesis; L, detected but below lower limit of determination.

OXIDE COATINGS ON FRACTURES, FAULTS, AND JOINTS IN THE BATAMOTE ANDESITE

As a test of the hypothesis that the Batamote anomaly could be caused by dispersion from material within or related to the normal faults, samples containing oxide coatings along fractures or joints within the Batamote Andesite were collected in both anomalous and background areas. Three samples (AJ136R, AJ152R, and AJ155R; sample sites 136, 152, and 155, respectively, on map B and in table 1) were collected in areas considered to be anomalous. Six samples (AJ162R through AJ167R; sample sites 162 and 167, respectively, on map B and in table 1) were collected from areas

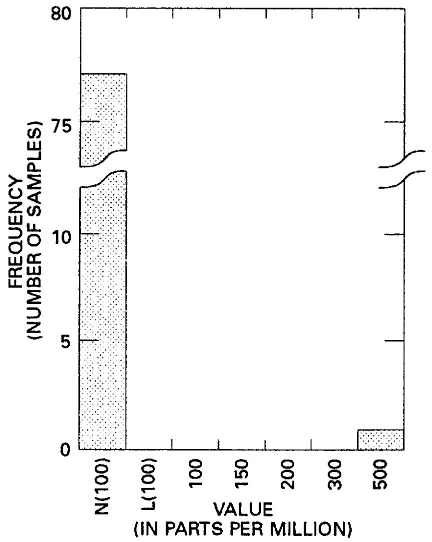


Figure 19. Histogram showing the distribution of zinc in the nonmagnetic C–3 fraction of heavy-mineral concentrates. N, not detected at lower limit of determination, given in parenthesis; L, detected but below lower limit of determination.

considered to be background. The oxide coatings were removed using a hot oxalic acid leach and were analyzed using semiquantitative emission spectrography. The results are reported in Huston (1984).

The anomalies of interest in stream sediments are characterized by copper, bismuth, and silver; therefore, this discussion will concentrate on these three elements. Copper and bismuth show a significant enrichment in the samples of oxide coatings collected in the anomalous areas, suggesting that these coatings are possible sources of bismuth and copper in anomalous stream sediments.

Conversely, the highest concentrations of silver are found in the non-anomalous areas. Yet the highest concentration of silver came from a sample in a drainage that has high silver in heavy-mineral concentrates—part of anomaly 3 described earlier.

Other elements that show enrichment in the oxide-coating samples from anomalous areas include arsenic, antimony, and tin. The detection limits of the analytical method used for analyzing stream sediments were not adequate to give usable results for these three elements in that sample media.

The enrichment of these elements—especially copper and bismuth—in oxide coatings from the anomalous areas is consistent with the hypothesis that the anomalous copper values in stream sediments are related to normal faults and fractures within at least the northwestern part of the study area.

SUMMARY AND CONCLUSIONS

The distribution of trace elements (principally copper, silver, and bismuth) in stream sediments and rocks in the Batamote Mountains was examined in this study to determine the cause of anomalous values of copper reported in Barton and others (1982).

Samples from the Batamote Andesite have a mean copper concentration of around 30 ppm, which is relatively low for rocks of similar composition. The values for copper have a limited range, implying that copper has a homogeneous distribution throughout the unit. The Batamote Andesite is the predominant bedrock unit in the study area; therefore, its copper concentration must control background copper concentrations in stream sediments from washes draining the mountains.

Analysis of stream sediments defined two anomalous areas which are characterized by the suite of copper, bismuth, and silver in the Batamote Mountains. The most significant anomaly, located in the northwestern part of the study area, is spatially associated with a series of north- to northeast-striking normal faults. The second anomaly, located in the north-central part of the study area, has no obvious fault control. The two anomalies are separated by only a narrow trough, and may be parts of a single larger anomaly. Because copper values do not vary significantly upstream from anomalous sample sites, the input of anomalous metals comes from throughout the drainage basins; therefore, the anomalies cannot be traced to a localized source.

Results from detailed sequential extractions imply that the copper in anomalous samples is held predominantly in a reducible (probably in oxides) state, although significant copper is held with sulfides or in some other "reduced" form in the heavies or slimes of stream sediments. Values of copper in the C–3 fraction of heavy-mineral concentrates are not high enough to account for copper values in stream sediments.

Analysis of pyrite grains extracted from the C–3 fraction of heavy-mineral concentrates demonstrates that the copper content of coarser grained pyrite cannot solely account for the copper anomalies observed in any sample medium.

Analysis of other elements in the C–3 fraction revealed three other anomalies that do not coincide with the stream-sediment anomalies. One anomaly, characterized by tin and molybdenum, occurs in an area where extensive alteration was observed in the Childs Latite. The other two anomalies, characterized by arsenic and antimony, and silver, molybdenum and arsenic, respectively, remained unexplained. No alteration, other than the presence of chalcedony and zeolites, was observed in these two areas.

Finally, analyses of oxide coatings from fractures and joints in both anomalous and non-anomalous areas (as determined from stream sediments) show that the oxide coatings in anomalous areas contain significantly more bismuth and copper than those in non-anomalous areas.

Evaluation of Working Hypotheses

In the introduction to this paper, five working hypotheses were presented as possible explanations for the anomalies observed by Barton and others (1982). In this section, the relative merit of each hypothesis is reviewed in the light of the data generated by this study.

Airborne Contamination from a Smelter in Ajo

It is the contention of the authors that smelter contamination cannot be the source of the anomalous metals (Cu-Ag-Bi, and maybe As-Sb-Sn); however, the data are equivocal.

Other studies of known smelter contamination indicate that such contamination is characterized by a rapid decrease in metal values downwind and down the soil profile (Rose and others, 1979). The same authors reported that soils within 1 km of the Superior, Arizona, smelter may contain as much as 5,000 ppm copper at the surface, but the values decrease to a background of 20 ppm at a depth of 15 cm. Canney (1959) reported evidence of smelter contamination 29 km downwind of the Kellogg, Idaho, smelter. Chemically, smelter contamination is characterized by a higher ratio of cold extractable versus total metals (Levinson, 1980).

Superficially, the areal and chemical dispersion patterns of copper in the Batamote Mountains appear to be consistent with smelter contamination. The areal distribution of copper could be inferred to be plumose in form, and the ratio of cold extractable copper to total copper for bulk stream sediments is significantly higher in anomalous samples than in background samples. (See discussion of second sequential extraction.) The lights contribute most significantly to the higher ratio of the anomalous samples. (This is consistent with other hypotheses, however.) In detail, however, the areal and chemical distributions argue against smelter contamination. In addition, the distribution of copper in different grain sizes also suggests a different genesis.

In the orientation study, high copper values persisted in anomalous samples in the coarser fractions of stream sediments. Although the values increased as grain size decreased, the minus-30/plus-80-mesh fraction contained high copper values. Smelter dust is fine grained, and copper values associated with smelter-dust contamination would be low in coarser fractions. For a typical smelter, 50 percent of the smelter dust passes through a 400-mesh screen and 80 percent of the dust passes through a 150-mesh screen (E. Partelpoeg, Phelps Dodge, personal commun., 1984). If the dust is weathered, which seems likely, the copper could be adsorbed onto larger grains, clays, or oxide coatings. The distribution of copper by grain size indicates that anomalous copper cannot be accounted for by unweathered smelter dust; however, weathering of smelter dust could produce the distribution of copper by grain size.

If copper from smelter dust was dispersed during the weathering cycle, the copper would be expected to concentrate in the less refractory chemical phases of the sediment (that is, the cold extractable fraction). But, in the slimes and heavies—and to a lesser extent the bulk and lights—of anomalous or borderline anomalous samples, much, if not most, of the copper is held in more chemically resistant fractions, especially the sulfide and (or) organic fraction. This is inconsistent with a smelter contamination source of copper.

Although the two anomalous areas determined from stream sediments could be interpreted to be part of a smelter plume, the fact that the copper values do not diminish significantly away from the smelter is inconsistent with this hypothesis. Anomalies derived from smelter contamination would be expected to decrease downwind, but copper values in stream sediments remain high throughout the northwestern and north-central Batamote Mountains.

Moreover, smelter contamination cannot explain most of the anomalies present in the C-3 fraction of heavy-mineral concentrates. In numerous samples from this medium, primary ore minerals were observed—they cannot be dismissed as smelter contamination.

Finally, two stream-sediment samples (AJ001S and AJ002S; sample sites 1 and 2, respectively, on map C) were collected in the Valley of the Ajo between the smelter and the mountains. They contained values of 170 and 90 ppm copper, respectively. AJ001S is anomalous based on total copper, but the distribution of copper among mineralogic phases (first sequential extraction) is significantly different from that of other anomalous samples, which indicates a totally different source of copper (Huston, 1984). On the other hand, AJ002S is borderline anomalous or background. Since its drainage lies downwind of the smelter and between the smelter and the anomaly, it would be expected to have a higher value if smelter contamination was significant. Rose and others (1979) reported copper values of 5,000 ppm in surficial soils 1 km from the Superior, Arizona, smelter.

These arguments suggest that airborne contamination from the smelter is an unlikely cause of the Batamote anomaly, but they are not unequivocal.

Thus, although smelter contamination is unlikely, it cannot be dismissed as a possible cause of the anomaly, especially in consideration of the amount of copper concentrate smelted at Ajo.

Abnormally High Background in the Batamote Andesite

Another possible source of copper is the bedrock. However, analyses of samples of the Batamote Andesite give a background value of around 30 ppm for copper. It seems unlikely that this unit could produce stream sediments that are as much as 280 ppm copper.

Primary Hydrothermal Mineralization

Primary hydrothermal mineralization alone could not account for the broad copper anomalies observed in stream sediments. Yet it best explains the three anomalies observed in the heavy-mineral concentrates. In many cases, the minerals that cause the anomalies include primary minerals. But in two of the anomalies, evidence for primary mineralization or hydrothermal alteration was not found.

Dispersion Along Normal Faults

Most evidence presented in this paper suggests that the anomalies observed in stream sediments were produced as the result of dispersion of metals from oxide coatings in faults and joints. Two principal pieces of evidence point to this mechanism. First, the anomalous values have a definite spatial association with the normal faults. Second, analyses of oxide coatings from fractures in the anomalous areas indicate that they are enriched relative to those from background areas.

On the other hand, entire drainages contribute significantly to the anomalies, which suggests that known faults were not the only contributors to the anomalies. Mineralized fractures and joints within the faulted northwestern area of the Batamote Mountains must contribute significant metal.

Contamination of the Batamote Andesite During Its Eruption

The mechanism involving contamination of the Batamote Andesite by wall rock before or during its eruption is also unlikely. The background values for the Batamote Andesite are too low to allow total assimilation of the hypothetical contaminant to be a cause. Additionally, the copper values show no zonation relative to the central vent from which the unit was extruded as might be expected from contamination without assimilation. This mechanism is considered unlikely.

Speculations About the Original Source of Copper

The preponderance of evidence presented in this paper suggests that the copper present in stream sediments in the northwestern part of the Batamote Mountains was derived from fracture and joint coatings in an area that is transected by several normal faults. Of a more interesting and significant nature is the original source of the anomalous metals observed in these structures. In this section, speculations are made about how the copper was originally deposited in the faults, fractures, and joints.

Possible sources of the metals in the faults, fractures, and joints include: (1) weathering processes that concentrated metals from background andesite into rinds along openings in the rock; (2) a higher water table that allowed groundwater to deposit the metals; (3) solutions migrating from the New Cornelia deposit; and (4) a shallow hydrothermal system in the Batamote Andesite that deposited metals which were weathered and deposited oxide coatings. This should not be considered an exhaustive list of sources as many other mechanisms could be called upon to deposit the metals.

Weathering can and does produce oxide coatings that significantly concentrate metals relative to their host rock. However, oxide coatings from the anomalous area contain more copper and bismuth than those from background areas. Presumably, weathering of the Batamote Andesite would be uniform throughout the study area; therefore it could not account for the great difference in metal concentrations observed in oxide coatings.

If a higher water table existed in the recent geologic past, solutions enriched in metals leached from rock below could provide the metals observed in the oxides. The original source of metals would have to be relatively close to, possibly directly below, the observed anomaly. This would be a reasonable mechanism to produce the metals in the faults, fractures, and joints.

The third possibility, lateral migration of supergene fluids from the New Cornelia orebody, is unlikely because of the long distance involved (as much as 10 miles), and because the observed metal assemblage in the stream sediments (Cu-Bi-Ag) differs from that observed around the orebody (Cu-Mo-Pb).

The fourth alternative, in which the primary metals were deposited by the distal part of a hydrothermal system and then were weathered and deposited into oxide coatings along fractures and joints, is considered