THE USE OF FACTOR ANALYSIS AS AN EXPLORATION TOOL IN PUERTO RICAN PORPHYRY COPPER DEPOSITS

by

Thomas H. Hickey

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Signed:
Thomas H. Hickey

Golden, Colorado
Date: March 7, 1986

Approved: Ronald W. Klusman
Ronald W. Klusman
Thesis Advisor

George H. Kennedy
George H. Kennedy
Head, Department of
Chemistry/Geochemistry

Golden, Colorado
Date: March 7, 1986

ABSTRACT

A study was made using soil samples collected over two porphyry copper deposits, Rio Tanama and Rio Vivi, located on the island of Puerto Rico. The soil samples were analyzed for elemental composition and the results were entered into a statistical analysis method called principal component analysis. Plotting the results of the principal component analysis over the known occurence of mineralization in both areas has shown that this type of analysis can provide an excellent method of delineating both mineralized porphyry and surrounding alteration zones associated with mineralization.

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INTRODUCTION

Economic porphyry copper mineralization in Puerto Rico was first discovered by Bear Creek Mining Company, a subsidiary of Kennecott Copper. Exploration programs delineated the North Tanama, South Tanama, and Helecho deposits in the mid-1950's (Lutjen, 1971).

In the latter part of 1957, Amax, operating through Ponce Mining Company, discovered the Pedro Hueca and Cala Abajo deposits of the Rio Vivi district. After drilling over 27 miles of core, the companies have estimated that the known deposits in both areas contain a total of 240 million tons of ore averaging 0.73% copper. There is also the possibiity of gold as a by-product during the extraction of copper from gangue material (Lutjen, 1971).

In the early 1970's, both Kennecott and Amax combined their efforts in Puerto Rico in an attempt to reduce the initial cost of mining and smelting operations. It was believed that this merger, along with the possibility of immediate benefit to the Puerto Rican economy, would speed efforts by the government to grant mining licenses to the two companies. Unfortunately, although all preliminary work was finished 18 years ago, no mining operations have begun due to problems with the Mining Commission and environmental groups (Lutjen, 1971).

The island of Puerto Rico can be split into three geologic provinces: limestone provinces with northern and southern sections; areas covered by surficial deposits; and a region underlain by an igneous complex (Barabas, 1977). These provinces are shown in Figure 1.

The porphyry copper deposits studied in this report are located along the southern border of the Utuado Batholith which is one of several batholiths in the igneous complex previously mentioned. The batholith is composed of granodiorite with a radiometric age of 65.9 ± 3.9 m.y., and the mineralized intrusives are quartz diorite porphyries 40.5 ± 2.8 m.y. (Barabas, 1977).

The known mineralization seems to occur where these Eocene porphyries have intruded along fault zones within the batholith or adjacent volcanics of the Robles Formation. The rocks in these fault zones show extensive hydrothermal alteration, and the porphyries themselves have been shattered and filled by quartz veins (Cox et al., 1973).

Economic mineralization is confined to two districts that are slightly more than 13 km apart. In each of the two districts, the northern deposits have undergone biotitic and weak propylitic alterations while the southern deposits have

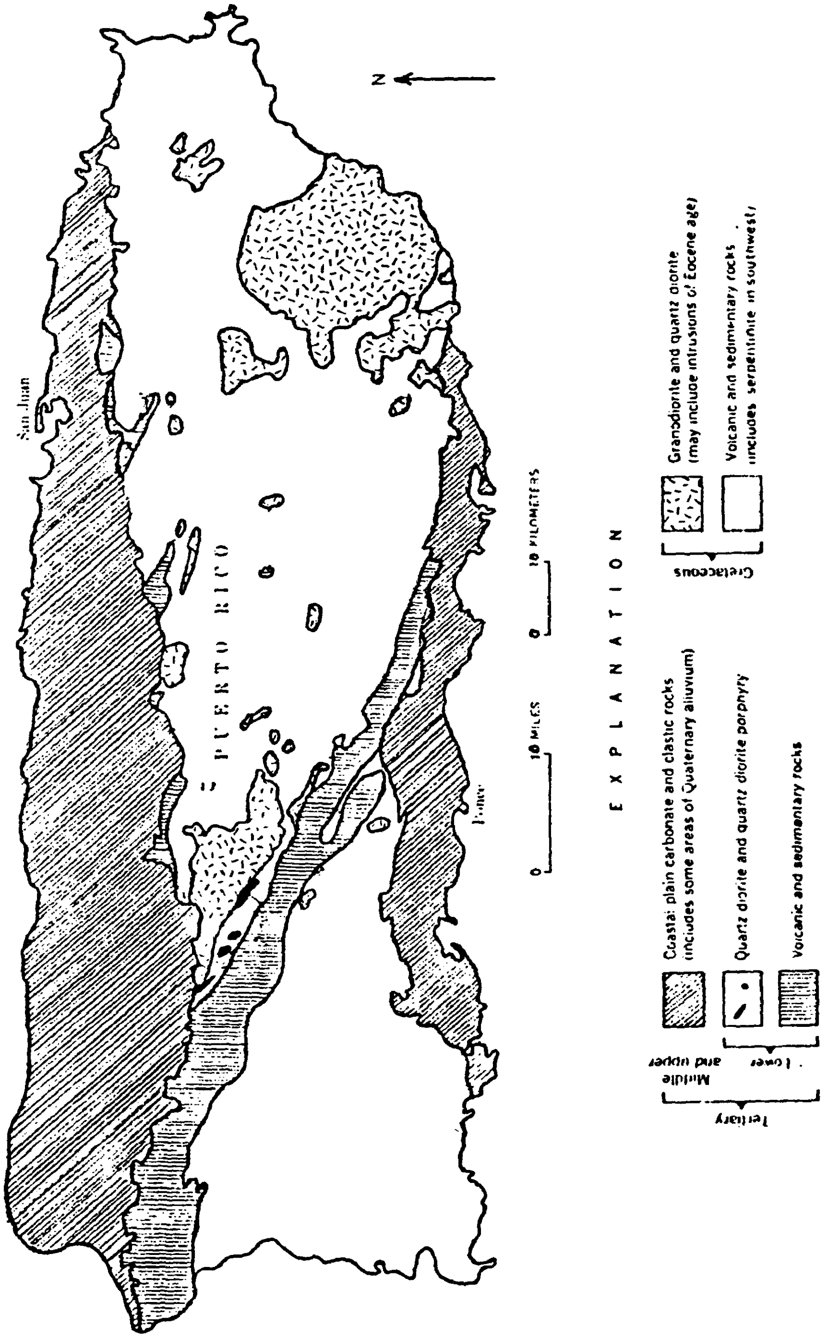

Figure 1. Geologic map of Puerto Rico (Cox, Larson, Tripp, 1975)

undergone extensive propylitic and sericitic alteration (Cox et al., 1973). Table 1 shows typical mineral assemblages found associated with the alteration around the copper deposits.

Although the deposits of the Rio Tanama district were discovered first, very little has been published about the area. The most notable publications to date include a paper describing the alteration types associated with Puerto Rican copper deposits (Cox et al., 1973) and a Ph.D. thesis describing petrologic properties and geologic characteristics of copper mineralization in central Puerto Rico (Barabas, 1977). Both of these studies contain discussions on alteration around the deposits but discuss little of the geochemical expression in the soils.

In contrast, the Rio Vivi district has been the subject of considerable publication since the first paper on the geology of the area by Amax field geologist R. Bradley (Bradley, 1971). The publications mentioned previously (Cox et al., 1973 and Barabas, 1977) both include discussions of the hydrothermal alteration around the deposis of the Rio Vivi district.

Learned and Boissen (1973) described the geochemical distribution of elements in soils around the deposits and found that gold can be a useful pathfinder element in

Table 1. Characteristic mineral assemblages associated with Puerto Rican Porphyry Copper Deposits (from Cox et al., 1973)

Alteration	Characteristic Assemblage
Biotitic	Quartz, Biotite, Chalcopyrite Pyrite, Magnetite, Potassium Feldspar
Propylitic	Chlorite, Epidote, Albite, Calcite, Rutile, Magnetite, Pyrite, Chalcopyrite
Sericitic	Quartz, Sericite, Albite, Chlorite, Epidote, Kaolinite, Pyrite, Chalcopyrite

finding mineralization similar to that found at Rio Vivi. The above authors discovered that soils can be used to map primary halos of Pb, Zn and Mn that extend outward from the deposits. An article on fluid inclusion petrography (Cox et al., 1975) describes in detail the alteration around the Sapo Alegre prospect including temperatures and salinity of the mineralizing solutions.

Objective of the Research

There has been much discussion on how effective factor analysis can be in mineral exploration programs. Much of the criticism concerning factor analysis can be attributed to the complexity of the method and the limited number of cases where it has been successfully used. The purpose of this research was to address several questions concerning factor analysis and how it can be used in the delineation of mineral deposits in Puerto Rico.

The most important question to be answered was whether factor analysis can actually extract information that is hidden in the subtle variances in the data not typically identified by other methods. This information is often difficult for a geologist to identify due to the amount of data to be analyzed in a typical geochemical survey.

Another question to be answered is whether this method is cost effective in terms of both real dollars spent in computer processing and time invested by a geologist in learning and using the method.

Sample Collection and Preparation

All the data for both districts were collected under the supervision of Robert Learned of the U.S.G.S. and a previous study (Learned and Boissen, 1973) describes in detail the sampling and analytical procedure used in the Rio Vivi district. An identical procedure was used in the Tanama district, and a summary of the sampling procedures for both follows.

Samples in the two areas were collected from the B soil horizon along ridges and spurs. The sampling interval varied, but in most cases, the interval was approximately 50 meters. This sampling design provided samples that were representative of residual soils and homogeneous in composition due to similarity of origin.

Samples were prepared by drying at about 110°C, and then passed through a jaw crusher to break agregates. Prior to analysis the samples were ground by use of a vertical pulverizer to minus 100 mesh with ceramic plates (Learned and Boissen, 1973).

The elements gold, copper, lead and zinc were analyzed by atomic absorption. Gold was analyzed by taking a 2.0 gram split and igniting it for one hour in a porcelain evaporating dish until ashed. The ashed sample was then dissolved overnight in a solution of hydrobromic acid and sodium bromate. The gold was then extracted from the solution with methyl isobutyl ketone (MIBK) and analyzed by atomic absorption (Thompson, Nakagawa, and Van Sickle, 1968).

Copper, lead and zinc were analyzed by dissolving a 1.0 gram split of the sample in boiling concentrated nitric acid for 30 minutes. The solution was then diluted to 10 ml and analyzed by atomic absorption (Ward et al., 1969).

All other elements were analyzed by semiquantitative spectrographic analysis. In each case a 10 mg sample was ground to less than 100 mesh and mixed thoroughly with 20 mg of pure graphite. The mixture was transferred to the cavity of an electrode and arced for 120 seconds. An estimate of the concentration of an element is based upon the intensity of the spectral lines of the unknown as compared to the spectra of standard samples (Grimes and Marranzino, 1968).

DATA TREATMENT

Frequently geochemical samples contain qualified data. Qualified data are data that are outside the detection limits of the analytical method used, and are in the form of a letter code preceded by a numerical value of the detection limit. In this study there are only three types of qualified values: N, L and G. A code of "N" indicates that the element under study is well below the detection limit in that sample. An "L" indicates the element was present, but was in amounts below which the method is capable of reporting accurately. A "G" indicates that the element was present in amounts greater than the method is capable of reporting accurately.

Table 2. Replacement procedure for qualified data (Qualified and replaced values in ppm.)

Qualified Value	Multiplier	Replaced Value
10N	.5	5
10L	.7	7
100G	1.5	150

Before a statistical analysis could be run on the data, all qualified values had to be replaced with unqualified values. Table 2 shows how the replacement program works with examples for each of the qualified codes. Although this presents the possibility of increasing the mean and standard deviation, the replacement procedure used is one which is practiced by most geologists and supported by geostatisticians (Koch and Link, 1971 and Davis, 1973).

Variables which had a greater proportion of qualified values than unqualified values were removed from the data sets prior to further analysis. These variables were removed to reduce the possibility of correlations occurring between the variables due to the replacement process. The corrected versions were used in all subsequent calculations.

If the distribution of the original data is highly skewed, it is common practice in geochemistry to transform variables. This transformation should result in a more symmetrical distribution about the mean of the data and allows the data to be used for statistical analysis. A lognormal distribution of the variables was found to give the most bell-shaped curves for most variables in both data sets and all original concentration values were replaced by the log of the concentration.

Basic statistics and correlations were carried out using the U.S. Geological Survey's STATPAC library system. The results for both areas are shown in Tables 3 through 12. Data sets were run through a principal components

Table 3. Basic statistics of original data from Rio Tanama

Element	Minimum	Maximum	Mean	Deviation	Valid	L	N	G
AA-Au	0.01	5.60	0.11	0.29	533	7	7	0
AA-Cu	14.00	2900.00	298.10	374.35	547	0	0	0
AA-Pb	1.00	1000.00	32.43	66.92	547	0	0	0
AA-Zn	1.00	840.00	68.29	96.11	545	2	0	0
Spec Ag	0.50	5.00	0.78	0.78	56	0	491	0
Spec Ba	20.00	2000.00	242.90	274.90	536	7	4	0
Spec Co	5.00	300.00	14.22	21.05	307	21	219	0
Spec Cr	5.00	3000.00	264.10	394.51	545	0	1	1
Spec Mn	10.00	5000.00	378.80	530.49	540	1	0	6
Spec Mo	5.00	700.00	30.91	74.17	175	48	324	0
Spec Ni	5.00	1500.00	60.01	127.33	413	126	8	0
Spec Sc	5.00	100.00	27.92	16.69	545	0	0	2
Spec V	30.00	1000.00	222.90	114.12	547	0	0	0
Spec Y	10.00	200.00	16.37	15.17	321	13	213	0
Spec Zr	10.00	700.00	97.59	57.27	547	0	0	0
Spec Mg	0.02	3.00	0.36	0.29	547	0	0	0
Spec Ti	0.01	1.00	0.40	0.19	546	0	0	1

Table 4. Basic statistics of original data from Rio Vivi

Element	Minimum	Maximum	Mean	Deviation	Valid	L	N	G
AA-Au	0.02	0.64	0.09	0.01	222	409	0	0
AA-Cu	5.00	5700.00	344.70	586.29	631	0	0	0
AA-Pb	1.00	189.00	13.54	17.17	629	2	0	0
AA-Zn	1.00	1000.00	61.22	89.48	626	5	0	0
Spec Ag	0.05	1.50	0.63	0.24	107	1	523	0
Spec Ba	20.00	1500.00	192.90	188.63	627	4	0	0
Spec Co	5.00	200.00	14.40	15.66	367	20	244	0
Spec Cr	1.00	5000.00	134.40	358.92	582	10	39	0
Spec Mn	1.00	5000.00	433.70	575.22	615	12	0	4
Spec Mo	5.00	1000.00	32.14	102.41	214	44	373	0
Spec Ni	5.00	1000.00	44.51	113.70	436	182	13	0
Spec Sc	3.00	100.00	19.65	12.56	630	0	0	1
Spec V	50.00	1000.00	165.90	78.72	621	0	0	0
Spec Y	10.00	100.00	18.98	9.97	464	6	161	0
Spec Zr	10.00	1000.00	113.20	76.21	631	0	0	0
Spec Mg	0.02	5.00	0.48	0.52	629	2	0	0
Spec Ti	0.10	1.00	0.33	0.18	631	0	0	0

Table 5. Basic statistics of replaced data from Rio Tanama

Element	Minimum	Maximum	Mean	Deviation	Valid	L	N	G
AA-Au	0.01	5.60	0.10	0.29	547	0	0	0
AA-Cu	14.00	2900.00	298.10	374.35	547	0	0	0
AA-Pb	1.00	1000.00	32.43	66.92	547	0	0	0
AA-Zn	0.70	840.00	68.05	96.01	547	0	0	0
Spec Ag	0.25	5.00	0.30	0.29	547	0	0	0
Spec Ba	10.00	2000.00	238.20	274.03	547	0	0	0
Spec Co	2.50	300.00	9.12	16.79	547	0	0	0
Spec Cr	5.00	4500.00	276.20	491.63	547	0	0	0
Spec Mn	7.00	7500.00	452.40	880.50	547	0	0	0
Spec Mo	2.50	700.00	11.68	43.90	547	0	0	0
Spec Ni	2.50	1500.00	46.16	113.25	547	0	0	0
Spec Sc	5.00	150.90	28.34	18.05	547	0	0	0
Spec V	30.00	1000.00	222.90	114.12	547	0	0	0
Spec Y	5.00	200.00	11.72	12.87	547	0	0	0
Spec Zr	10.00	700.00	97.59	57.27	547	0	0	0
Spec Mg	0.02	3.00	0.36	0.29	547	0	0	0
Spec Ti	0.10	1.50	0.40	0.20	547	0	0	0

Table 6. Correlations of replaced data from Rio Tanama

					SPEC												
	AA-Au	AA-Cu	AA-Pb	AA-Zn	Ag	Ba	Co	Cr	Mn	Mo	Ni	Sc	V	Y	Zr	Mg%	Ti%
AA-Au	1.00	0.33	-0.05	-0.11	-0.00	-0.12	0.00	-0.05	-0.00	-0.01	-0.06	-0.06	-0.09	-0.06	0.03	-0.02	-0.05
AA-Cu	0.33	1.00	-0.01	-0.06	0.03	-0.09	0.18	0.10	0.08	0.09	0.01	0.23	0.08	0.16	-0.02	0.30	0.05
AA-Pb	-0.05	-0.01	1.00	0.30	0.11	0.15	0.04	0.06	0.17	-0.04	0.03	0.05	0.10	0.02	0.02	0.05	0.06
AA-Zn	-0.11	-0.06	0.30	1.00	0.18	0.17	0.19	0.09	0.54	-0.12	0.13	0.01	0.02	0.07	-0.09	0.04	-0.08
Ag	-0.00	0.03	0.11	0.18	1.00	0.04	0.00	0.00	0.05	-0.03	-0.02	0.01	0.00	0.03	-0.01	-0.03	-0.04
Ba	-0.12	-0.09	0.15	0.17	0.04	1.00	-0.01	-0.06	0.26	0.03	-0.03	0.07	0.31	0.19	0.26	0.30	0.29
Co	0.00	0.18	0.04	0.19	0.00	-0.01	1.00	0.24	0.41	-0.06	0.42	0.10	0.06	0.09	-0.06	0.25	-0.04
Cr	-0.05	0.10	0.06	0.09	0.00	-0.06	0.24	1.00	0.09	-0.01	0.65	0.37	0.26	0.05	-0.02	0.42	0.18
Mn	-0.00	0.08	0.17	0.54	0.05	0.26	0.41	0.09	1.00	-0.02	0.27	0.08	0.12	0.10	0.02	0.18	0.09
Mo	-0.01	0.09	-0.04	-0.12	-0.03	0.03	-0.06	-0.01	-0.02	1.00	-0.05	0.10	0.02	0.02	0.02	0.02	0.18
Ni	-0.06	0.01	0.03	0.13	-0.02	-0.03	0.42	0.65	0.27	-0.05	1.00	0.23	0.16	0.00	-0.11	0.38	0.05
Sc	-0.06	0.23	0.05	0.01	0.01	0.07	0.10	0.37	0.08	0.10	0.23	1.00	0.51	0.15	-0.03	0.27	0.45
V	-0.09	0.08	0.10	0.02	0.00	0.31	0.06	0.26	0.12	0.02	0.16	0.51	1.00	0.17	0.25	0.38	0.61
Y	-0.06	0.16	0.02	0.07	0.03	0.19	0.09	0.05	0.10	0.02	0.00	0.15	0.17	1.00	0.23	0.28	0.27
Zr	0.03	-0.02	0.02	-0.09	-0.01	0.26	-0.06	-0.02	0.02	0.02	-0.11	-0.03	0.25	0.23	1.00	0.21	0.37
Mg	-0.02	0.30	0.05	0.04	-0.03	0.03	0.25	0.42	0.18	0.02	0.38	0.27	0.38	0.28	0.21	1.00	0.28
Ti	-0.05	0.05	0.06	-0.08	-0.04	0.29	-0.04	0.18	0.09	0.13	0.05	0.45	0.61	0.27	0.37	0.28	1.00

Table 7. Basic statistics of replaced data from Rio Vivi

Element	Minimum	Maximum	Mean	Deviation	Valid	L	N	G
AA-Au	0.01	0.64	0.05	0.07	632	0	0	0
AA-Cu	5.00	5700.00	344.70	585.83	632	0	0	0
AA-Pb	0.70	189.00	13.50	17.15	632	0	0	0
AA-Zn	0.70	1000.00	60.74	89.22	632	0	0	0
Spec Ag	0.25	1.50	0.31	0.17	632	0	0	0
Spec Ba	14.00	1500 00	191.80	188.41	632	0	0	0
Spec Co	2.50	200.00	9.46	13.28	632	0	0	0
Spec Cr	5.00	5000.00	124.70	346.02	632	0	0	0
Spec Mn	7.00	7500.00	468.00	780.76	632	0	0	0
Spec Mo	2.50	1000.00	12.66	61.13	632	0	0	0
Spec Ni	2.50	1000.00	31.88	96.28	632	0	0	0
Spec Sc	3.00	150.00	19.84	13.47	632	0	0	0
Spec V	50.00	1000.00	165.90	78.04	632	0	0	0
Spec Y	5.00	100.00	15.30	10.52	632	0	0	0
Spec Zr	10.00	1000.00	113.20	76.15	632	0	0	0
Spec Mg	0.01	5.00	0.48	0.52	632	0	0	0
Spec Ti	0.10	1.00	0.33	0.18	632	0	0	0

Table 8. Correlations of replaced data from Rio Vivi

					SPEC												
	AA-Au	AA-Cu	AA-Pb	AA-Zn	Ag	Ba	Co	Cr	Mn	Mo	Ni	Sc	V	Y	Zr	Mg%	Ti%
AA-Au	1.00	0.33	-0.01	-0.01	0.36	-0.09	-0.05	-0.06	-0.08	0.02	-0.08	-0.14	-0.11	-0.11	0.02	-0.04	-0.06
AA-Cu	0.33	1.00	-0.01	0.03	0.47	0.05	0.10	0.11	0.09	0.02	0.08	0.09	0.04	0.06	-0.06	0.22	0.02
AA-Pb	-0.01	-0.01	1.00	0.32	0.15	-0.06	0.06	0.10	0.19	-0.08	0.07	0.03	-0.05	-0.09	-0.17	-0.02	-0.10
AA-Zn	-0.10	0.03	0.32	1.00	0.13	0.09	0.32	0.13	0.53	-0.10	0.20	0.20	0.03	0.10	-0.22	0.30	-0.07
Ag	0.36	0.47	0.15	0.13	1.00	0.07	0.13	0.14	0.17	0.14	0.08	0.12	0.05	0.10	-0.08	0.19	0.05
Ba	-0.09	0.05	-0.06	0.09	0.07	1.00	0.21	0.21	0.27	0.01	0.25	0.27	0.24	0.32	0.12	0.36	0.24
Co	-0.05	0.10	0.06	0.32	0.13	0.21	1.00	0.67	0.41	-0.08	0.71	0.42	0.22	0.25	-0.20	0.63	-0.02
Cr	-0.06	0.11	0.10	0.13	0.14	0.21	0.67	1.00	0.29	0.01	0.83	0.55	0.44	0.13	-0.13	0.63	0.17
Mn	-0.08	0.09	0.19	0.53	0.17	0.27	0.41	0.29	1.00	-0.02	0.41	0.37	0.22	0.24	-0.11	0.47	0.15
Mo	0.02	0.02	-0.08	-0.10	0.14	0.01	-0.08	0.01	-0.08	1.00	-0.03	-0.06	-0.05	0.04	0.02	-0.06	-0.01
Ni	-0.08	0.08	0.07	0.20	0.08	0.25	0.71	0.83	0.41	-0.03	1.00	0.43	0.34	0.16	-0.15	0.71	0.10
Sc	-0.14	0.09	0.03	0.20	0.12	0.27	0.42	0.55	0.37	-0.06	0.43	1.00	0.67	0.36	0.02	0.50	0.51
V	-0.11	0.04	-0.05	0.03	0.05	0.24	0.22	0.44	0.22	-0.05	0.34	0.67	1.00	0.26	0.14	0.42	0.59
Y	-0.11	0.06	-0.09	0.10	0.10	0.32	0.25	0.13	0.24	0.04	0.16	0.36	0.26	1.00	0.25	0.31	0.36
Zr	0.02	-0.06	-0.17	-0.22	-0.08	0.12	-0.20	-0.13	-0.11	0.02	-0.15	0.02	0.14	0.25	1.00	-0.18	0.41
Mg	-0.04	0.22	-0.02	0.30	0.19	0.36	0.63	0.63	0.47	-0.06	0.71	0.50	0.42	0.31	-0.19	1.00	0.12
Ti	-0.06	0.02	-0.10	-0.07	0.05	0.24	-0.02	0.17	0.15	-0.01	0.10	0.51	0.59	0.36	0.41	0.12	1.00

Table 9. Basic statistics of log-transformed data from Rio Tanama

Element	Minimum	Maximum	Mean	Deviation	Valid	L	N	G
AA-Au	-2.00	0.75	-1.32	0.42	547	0	0	0
AA-Cu	1.15	3.46	2.25	0.43	547	0	0	0
AA-Pb	0.00	3.00	1.29	0.38	547	0	0	0
AA-Zn	-0.15	2.98	1.49	0.58	547	0	0	0
Spec Ag	-0.61	0.70	-0.56	0.14	547	0	0	0
Spec Ba	1.00	3.30	2.15	0.45	547	0	0	0
Spec Co	0.40	2.48	0.75	0.38	547	0	0	0
Spec Cr	0.70	3.85	2.04	0.59	547	0	0	0
Spec Mn	0.85	3.85	2.26	0.59	547	0	0	0
Spec Mo	0.40	2.85	0.65	0.43	547	0	0	0
Spec Ni	0.40	3.18	1.23	0.57	547	0	0	0
Spec Sc	0.70	2.16	1.39	0.23	547	0	0	0
Spec V	1.48	3.00	2.30	0.21	547	0	0	0
Spec Y	0.70	2.30	0.97	0.26	547	0	0	0
Spec Zr	1.00	2.85	1.93	0.23	547	0	0	0
Spec Mg	-1.70	0.48	-0.58	0.36	547	0	0	0
Spec Ti	-1.00	0.15	-4.46	0.22	547	0	0	0

Table 10. Correlations of log-transformed data from Rio Tanama

					SPEC												
	AA-Au	AA-Cu	AA-Pb	AA-Zn	Ag	Ba	Co	Cr	Mn	Mo	Ni	Sc	V	Y	Zr	Mg%	Ti%
AA-Au	1.00	0.54	-0.19	-0.29	0.10	-0.15	-0.02	-0.06	-0.07	0.17	-0.20	-0.15	-0.13	-0.10	0.11	-0.07	-0.02
AA-Cu	0.54	1.00	0.01	-0.09	0.10	0.05	0.23	0.21	0.05	0.26	0.11	0.26	0.17	0.09	0.04	0.26	0.13
AA-Pb	-0.19	0.01	1.00	0.58	0.19	0.18	0.23	0.25	0.42	-0.27	0.32	0.10	0.20	0.03	0.02	0.15	0.03
AA-Zn	-0.29	-0.09	0.58	1.00	0.19	-0.03	0.51	0.24	0.73	-0.48	0.49	0.05	0.04	-0.05	-0.17	0.08	-0.16
Ag	0.10	0.10	0.19	0.19	1.00	0.05	0.10	0.11	0.17	-0.07	0.07	0.08	0.04	0.09	-0.02	0.02	-0.01
Ba	-0.15	0.05	0.18	-0.03	0.05	1.00	-0.10	-0.01	-0.02	0.23	-0.13	0.17	0.34	0.47	0.41	0.46	0.35
Co	-0.02	0.23	0.23	0.51	0.10	-0.10	1.00	0.31	0.61	-0.24	0.60	0.16	0.05	0.03	-0.20	0.28	-0.16
Cr	-0.06	0.21	0.25	0.24	0.11	-0.01	0.31	1.00	0.13	-0.00	0.65	0.49	0.43	0.16	0.06	0.29	0.25
Mn	-0.07	0.05	0.42	0.73	0.17	-0.02	0.61	0.13	1.00	-0.36	0.45	0.12	0.03	-0.06	-0.11	0.17	-0.05
Mo	0.17	0.26	-0.27	-0.48	-0.07	0.23	-0.24	-0.00	-0.36	1.00	-0.23	0.16	0.15	0.22	0.17	0.17	0.28
Ni	-0.20	0.11	0.32	0.49	0.07	-0.13	0.60	0.65	0.45	-0.23	1.00	0.41	0.29	-0.03	-0.14	0.27	0.08
Sc	-0.15	0.26	0.10	0.05	0.08	0.17	0.16	0.49	0.12	0.16	0.41	1.00	0.67	0.27	0.03	0.37	0.51
V	-0.13	0.17	0.20	0.04	0.04	0.34	0.05	0.43	0.03	0.15	0.29	0.67	1.00	0.34	0.32	0.42	0.66
Y	-0.10	0.09	0.03	-0.05	0.09	0.47	0.03	0.16	-0.06	0.22	-0.03	0.27	0.34	1.00	0.39	0.37	0.41
Zr	0.11	0.04	0.02	-0.17	-0.02	0.41	-0.20	0.06	-0.11	0.17	-0.14	0.03	0.32	0.39	1.00	0.27	0.50
Mg	-0.07	0.26	0.15	0.08	0.02	0.46	0.28	0.29	0.17	0.17	0.27	0.37	0.42	0.37	0.27	1.00	0.31
Ti	-0.02	0.13	0.03	-0.16	-0.01	0.35	-0.16	0.25	-0.05	0.28	0.09	0.51	0.66	0.41	0.50	0.31	1.00

Table 11. Basic statistics of log-transformed from data Rio Vivi

Element	Minimum	Maximum	Mean	Deviation	Valid	L	N	G
AA-Au	-1.85	-0.19	-1.51	0.35	632	0	0	0
AA-Cu	0.70	3.76	2.21	0.52	632	0	0	0
AA-Pb	-0.15	2.28	0.98	0.34	632	0	0	0
AA-Zn	-0.15	3.00	1.41	0.63	632	0	0	0
Spec Ag	-0.60	0.18	-0.54	0.15	632	0	0	0
Spec Ba	1.15	3.18	2.15	0.34	632	0	0	0
Spec Co	0.40	2.30	0.78	0.38	632	0	0	0
Spec Cr	0.70	3.70	1.57	0.56	632	0	0	0
Spec Mn	0.85	3.85	2.24	0.67	632	0	0	0
Spec Mo	0.40	3.00	0.64	0.41	632	0	0	0
Spec Ni	0.40	3.00	1.01	0.52	632	0	0	0
Spec Sc	0.48	2.16	1.23	0.25	632	0	0	0
Spec V	1.70	3.00	2.18	0.18	632	0	0	0
Spec Y	0.70	2.00	1.09	0.29	632	0	0	0
Spec Zr	1.00	3.00	1.98	0.27	632	0	0	0
Spec Mg	-1.85	0.70	-0.53	0.46	632	0	0	0
Spec Ti	-1.00	0.00	-0.54	0.23	632	0	0	0

Table 12. Correlations of log-transformed data from Rio Vivi

					SPEC												
	AA-Au	AA-Cu	AA-Pb	AA-Zn	Ag	Ba	Co	Cr	Mn	Mo	Ni	Sc	V	Y	Zr	Mg%	Ti%
AA-Au	1.00	0.30	0.12	-0.05	0.30	-0.26	-0.04	-0.10	-0.08	0.16	-0.11	-0.23	-0.21	-0.15	-0.09	-0.04	-0.21
AA-Cu	0.30	1.00	0.05	0.06	0.46	0.04	0.17	0.36	0.18	0.19	0.27	0.24	0.13	0.16	-0.04	0.33	0.13
AA-Pb	0.12	0.05	1.00	0.62	0.12	-0.12	0.29	0.02	0.46	-0.38	0.29	0.02	-0.11	-0.22	-0.28	0.14	-0.25
AA-Zn	-0.05	0.06	0.62	1.00	0.18	0.06	0.67	0.03	0.82	-0.54	0.48	0.19	-0.04	-0.01	-0.42	0.50	-0.26
Ag	0.30	0.46	0.12	0.18	1.00	0.08	0.23	0.18	0.25	0.06	0.20	0.13	0.06	0.11	-0.07	0.29	0.07
Ba	-0.26	0.04	-0.12	0.06	0.08	1.00	0.15	0.20	0.21	0.04	0.12	0.31	0.24	0.38	0.22	0.34	0.32
Co	-0.04	0.17	0.29	0.67	0.23	0.15	1.00	0.23	0.74	-0.34	0.63	0.33	0.12	0.21	-0.37	0.60	-0.13
Cr	-0.10	0.36	0.02	0.03	0.18	0.20	0.23	1.00	0.17	0.16	0.71	0.58	0.58	0.28	-0.00	0.37	0.43
Mn	-0.08	0.18	0.46	0.82	0.25	0.21	0.74	0.17	1.00	-0.49	0.57	0.31	0.08	0.11	-0.29	0.64	-0.06
Mo	0.16	0.19	-0.38	-0.54	0.06	0.04	-0.34	0.16	-0.49	1.00	-0.19	-0.07	0.05	0.11	0.20	-0.17	0.19
Ni	-0.11	0.27	0.29	0.48	0.20	0.12	0.63	0.71	0.57	-0.19	1.00	0.50	0.39	0.19	-0.31	0.55	0.12
Sc	-0.23	0.24	0.02	0.19	0.13	0.31	0.33	0.58	0.31	-0.07	0.50	1.00	0.68	0.49	0.10	0.45	0.55
V	-0.21	0.13	-0.11	-0.04	0.06	0.24	0.12	0.58	0.08	0.05	0.39	0.68	1.00	0.39	0.22	0.31	0.64
Y	-0.15	0.16	-0.22	-0.01	0.11	0.38	0.21	0.28	0.11	0.11	0.19	0.49	0.39	1.00	0.26	0.34	0.46
Zr	-0.09	-0.04	-0.28	-0.42	-0.07	0.22	-0.37	-0.00	-0.29	0.20	-0.31	0.10	0.22	0.26	1.00	-0.21	0.52
Mg	-0.04	0.33	0.14	0.50	0.29	0.34	0.60	0.37	0.64	-0.17	0.55	0.45	0.31	0.34	-0.21	1.00	0.11
Ti	-0.21	0.13	-0.25	-0.26	0.07	0.32	-0.13	0.43	-0.06	0.19	0.12	0.55	0.64	0.46	0.52	0.11	1.00

analysis program, ERMODE, written by Alfred Miesch of the U.S. Geological Survey. The results of the analysis are presented in Tables 13 and 14.

Table 13. Principal componant loadings, multiple correlations, eigenvalues, and cpm - Rio Tanama

	Principal Component Loadings				Variable Communalities				Multiple Correlations	
Element	1	2	3	4	1	2	3	4	Coeff.	Square
AA-Au	-0.2080	0.1747	0.7201	-0.4139	0.0433	0.0738	0.5324	0.7637	0.7190	0.5169
AA-Cu	0.2634	0.2005	0.7579	-0.2974	0.0694	0.1036	0.6840	0.7725	0.7062	0.4987
AA-Pb	0.4994	-0.3478	-0.2815	-0.2641	0.2494	0.3704	0.4496	0.5193	0.6516	0.4246
AA-Zn	0.4976	-0.6924	-0.2313	-0.1843	0.2476	0.7270	0.7805	0.8145	0.8497	0.7220
Spec Ag	0.1973	-0.1252	0.1005	-0.3841	0.0389	0.0546	0.0647	0.2122	0.3284	0.1079
Spec Ba	0.3446	0.4914	-0.4053	-0.3972	0.1188	0.3603	0.5246	0.6823	0.6854	0.4697
Spec Co	0.5216	-0.5256	0.2805	-0.1375	0.2721	0.5484	0.6271	0.6460	0.7877	0.6204
Spec Cr	0.6710	-0.0350	0.2574	0.3452	0.4503	0.4515	0.5178	0.6369	0.7422	0.5659
Spec Mn	0.4992	-0.5955	-0.0255	-0.3163	0.2492	0.6038	0.6043	0.7043	0.8232	0.6776
Spec Mo	-0.0544	0.6554	0.2654	0.0239	0.0030	0.4324	0.5029	0.5035	0.6040	0.3648
Spec Ni	0.6953	-0.4191	0.1855	0.3142	0.4835	0.6591	0.6835	0.7922	0.8319	0.6921
Spec Sc	0.6846	0.2645	0.1673	0.3898	0.4686	0.5386	0.5666	0.7185	0.7908	0.6254
Spec V	0.6935	0.4271	-0.0534	0.2355	0.4809	0.6633	0.6662	0.7216	0.8016	0.6426
Spec Y	0.4021	0.4960	-0.2234	-0.2298	0.1609	0.4070	0.4569	0.5097	0.6259	0.3918
Spec Zr	0.2104	0.5733	-0.2292	-0.3235	0.0443	0.3730	0.4255	0.5302	0.6711	0.4503
Spec Mg	0.6200	0.2843	0.0190	-0.1964	0.3844	0.4652	0.4655	0.5041	0.6627	0.4391
Spec Ti	0.4879	0.6270	-0.0984	-0.1254	0.2381	0.6312	0.6409	0.6566	0.7844	0.6153
Eigenvalue	4.0026	3.4665	1.7937	1.4254						
CPM	0.2354	0.4394	0.5449	0.6287						

Table 14. Principal componant loadings, multiple correlations, eigenvalues, and cpm - Rio Vivi

	Principal Component Loadings				Variable Communalities				Multiple Correlations	
Element	1	2	3	4	1	2	3	4	Coeff.	Square
AA-Au	-0.1402	-0.2206	0.7258	0.0944	0.0197	0.0683	0.5951	0.6040	0.5535	0.3063
AA-Cu	0.3669	0.1396	0.7060	0.0790	0.1346	0.1541	0.6526	0.6589	0.6268	0.3929
AA-Pb	0.3551	-0.5650	0.0016	-0.1589	0.1232	0.4425	0.4425	0.4677	0.6996	0.4895
AA-Zn	0.6722	-0.6004	-0.1614	0.1013	0.4518	0.8123	0.8383	0.8486	0.8986	0.8075
Spec Ag	0.3493	-0.0157	0.6219	0.3095	0.1220	0.1223	0.5090	0.6048	0.5442	0.2961
Spec Ba	0.3407	0.3760	-0.2485	0.5291	0.1161	0.2575	0.3192	0.5992	0.5650	0.3192
Spec Co	0.7676	-0.3319	-0.0387	0.1139	0.5891	0.6993	0.7008	0.7138	0.8299	0.6887
Spec Cr	0.5985	0.4515	0.2130	-0.4653	0.3582	0.5621	0.6074	0.8239	0.8700	0.7570
Spec Mn	0.7914	-0.4022	-0.1245	0.1979	0.6263	0.7881	0.8036	0.8428	0.8967	0.8041
Spec Mo	-0.3159	0.4927	0.4705	-0.0301	0.0998	0.3426	0.5639	0.5648	0.6456	0.4168
Spec Ni	0.8211	-0.0285	0.0611	-0.3795	0.6742	0.6750	0.6788	0.8228	0.8902	0.7925
Spec Sc	0.6818	0.4814	-0.1086	-0.1337	0.4648	0.6965	0.7083	0.7262	0.7985	0.6376
Spec V	0.4823	0.6335	-0.1033	-0.2922	0.2326	0.6340	0.6447	0.7301	0.7868	0.6190
Spec Y	0.3934	0.5451	-0.0754	0.3656	0.1548	0.4519	0.4576	0.5912	0.6555	0.4297
Spec Zr	-0.2367	0.6256	-0.1358	0.2898	0.0560	0.4474	0.4658	0.5498	0.6763	0.4574
Spec Mg	0.7898	-0.0149	0.0772	0.2272	0.6239	0.6241	0.6300	0.6816	0.7758	0.6018
Spec Ti	0.2363	0.8067	-0.0936	-0.0119	0.0558	0.7065	0.7153	0.7154	0.8142	0.6630
Eigenvalue	4.9029	3.5814	1.8486	1.2127						
CPM	0.2884	0.4991	0.6078	0.6792						

PRINCIPAL COMPONENT ANALYSIS

In order to demonstrate how principal component analysis works, the following example will be used. Assume that soil samples have been collected in a area that contains only two rock types: a basalt, and a porphyry of granitic composition. A geologic and sample location map for the example is shown in Figure 2.

The mineralization in this example is found in the porphyritic intrusives and is characterized by high concentrations of copper and other base metals. Based on the associations of known porphyry copper mineralization, the elements copper, cobalt and manganese were chosen for analysis. The standardized values for the elements are plotted on the three dimensional scatter diagram shown in Figure 3.

The variables are standardized according to the equation:

$$\frac{\text{OBSERVED VALUE} - \text{MEAN}}{\text{STANDARD DEVIATION}}$$

Standardization transforms all the data such that each variable has a mean of zero and a standard deviation of one. By standardizing the data, it is possible to compare elements that have different ranges of values.

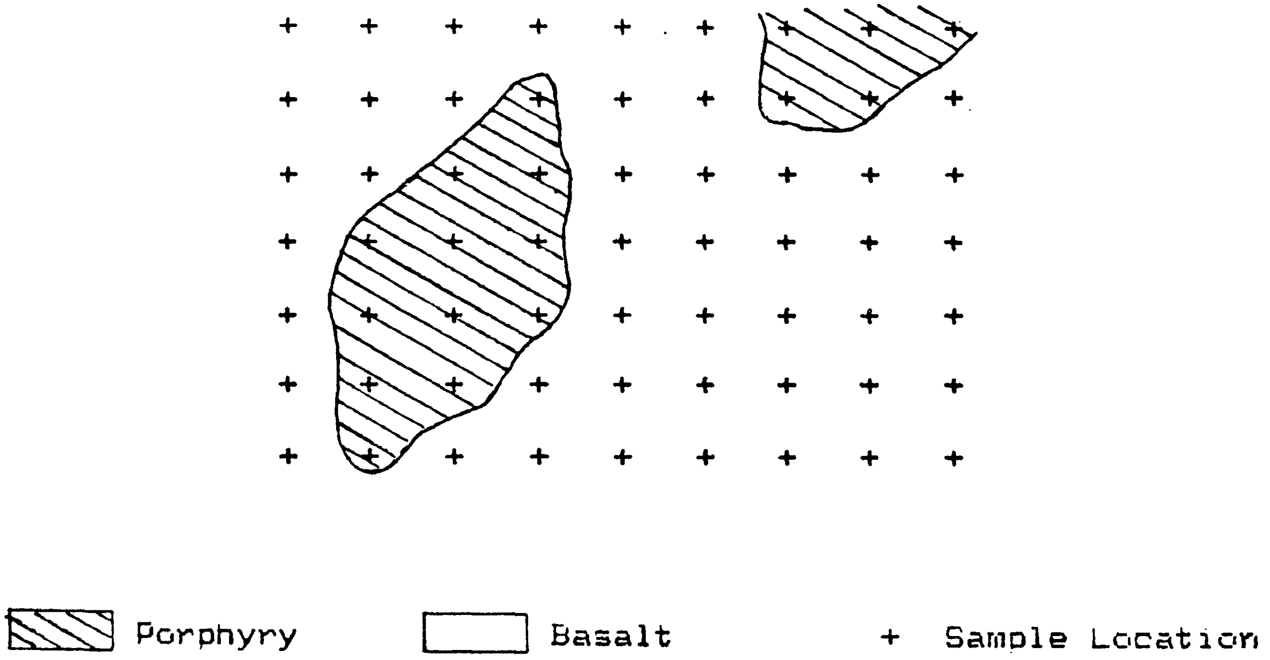

Figure 2. Geologic map and sample locations for hypothetical example

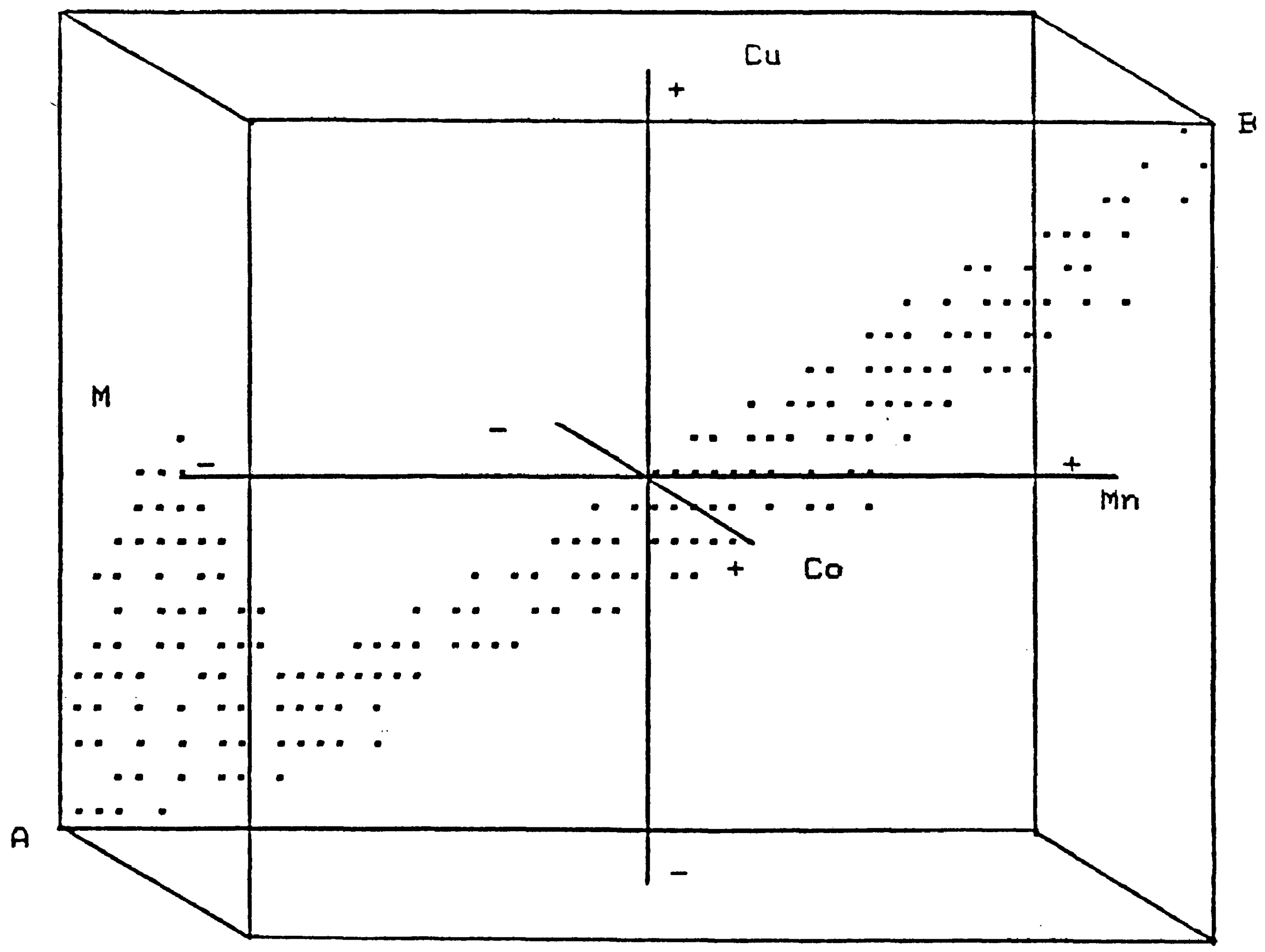

Figure 3. Three-dimensional scatter diagram for hypothetical example

In Figure 3, the samples that are located near point "M" indicate mineralization in the porphyry. The general trend of increasing values from point "A" to "B" indicates the ranges in the three elements in going from porphyry to basalt. The samples collected over porphyry would be lower than average in all three elements and would be found near point "A". Those samples collected over the basalt would be found near point "B" where the values of all three elements are higher than average.

Typically, mineralized samples are found statistically using the mean and standard deviation of a single element associated with mineralization. Elemental values greater than the mean and two standard deviations are considered highly anomalous, those greater than the mean and one standard deviation and less than two standard deviations are probably anomalous, and any between the mean and one standard deviation possibly anomalous (Rose, 1972).

In the example, the element used to determine mineralization would be copper due to its association with the known mineralization in the area. If the points of the scatter diagram (Figure 3) were all projected onto the copper axis, it can be seen that the mineralized samples would plot close to the mean. Using this method, mineralized samples would not be classified as being anomalous, whereas samples not related to mineralization would be classified as anomalous.

It should be apparent that in a situation as described above, the typical statistical methods used would be inadequate. Since the mineralized samples can easily be distinguished from the others in the scatter diagram, there should be a way of separating the mineralized from the non-mineralized samples.

It can be seen from Figure 3 that if a line were drawn from point "A" to "B", it would be possible to explain much of the variance in the data using only one axis instead of the original three axes. Figures 4 and 5 show two-dimensional views of the coordinate system obtained by using line AB as one of the axes. The other axes, labeled II and III in the diagram, were obtained by finding the largest remaining variance in the data and drawing an axis parallel to the variance and perpendicular to the other axes.

The axes of the new coordinate system no longer correspond to elemental concentrations but are interpreted to be related to processes that control the variance of the data. Axis I expresses the variance associated with the two different rock types in the area. Samples located at the positive end of the axis would be from the basalt and those at the negative end from the porphyry. The variance along

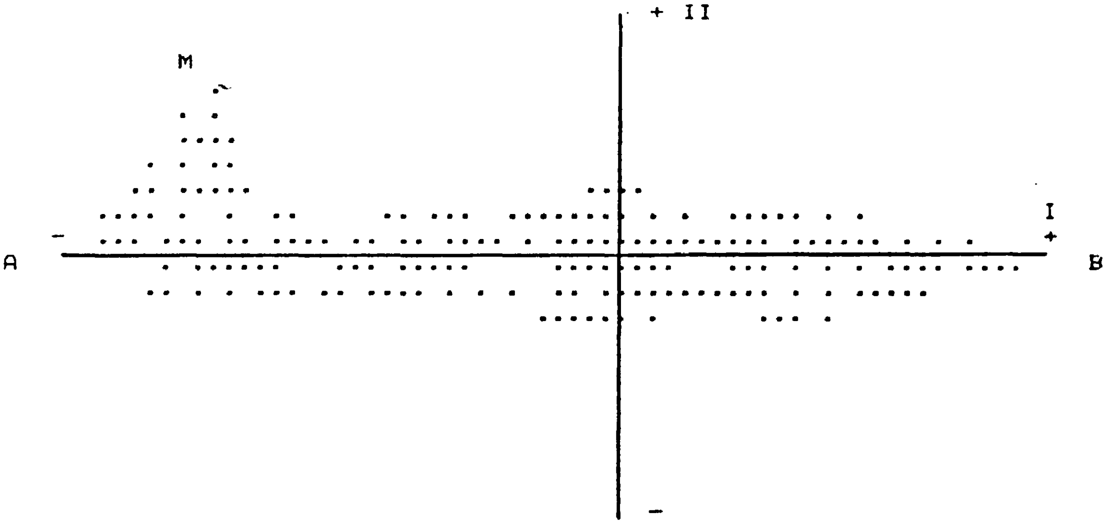

Figure 4. Points from figure 3 projected on to axis I and looking down axis III

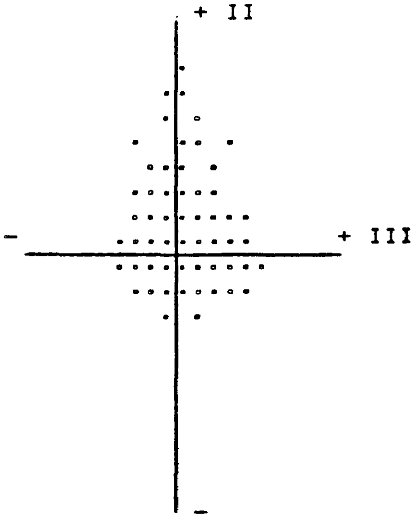

Figure 5. Projected points from figure 3 looking down axis I

axis II is clearly related to mineralization and any large positive values should delineate these areas. The variance in axis III does not appear to be related to any geologic process and is the smallest of the three. In this case, since all elemental determinations contain some inaccuracy, the variance in axis III is probably related to a combination of analytical and sampling errors.

The example displays a procedure similar to that found in principal component analysis and can be used to explain much of the complex terminology associated with this type of analysis. The new coordinate system developed in the example is not unlike that obtained with principal component analysis as the axes of the example are similar to eigenvectors obtained from the analysis. In principal component analysis, the eigenvectors are given the names principal component I, principal component II, etc.

Eienvalues represent the length of the principal components. Principal component I always has the largest eigenvalue, principal component II has the second largest eigenvalue and the last principal component has the smallest eigenvalue. Summing the lengths of the principal components will give a value that corresponds to the total variance of the data. If each principal component were divided by the sum of the components the percentage of variation explained by each eigenvalue can be determined, this is called the communality.

The loading of an element indicates how much of an influence that element has on a particular component. In the example, axis I is controlled by all three elements and principal component I would show high positive loadings for all three elements. Axis II is related to increasing concentrations of copper and decreasing concentrations of Co and Mn, and principal component II would have a high positive loading for Cu and negative loadings for Co and Mn. Axis III does not appear to correlate with any of the axes, and loadings for the three elements would be close to zero.

PREVIOUS STUDIES USING FACTOR ANALYSIS

One of the first studies to use factor analysis in a geochemical survey was that of Garrett and Nichol (1969). In this study, stream sediment samples were used in an R-mode factor analysis. It was concluded that several of the factors could be related to geologic processes, and that factor analysis could serve as an aid in geologic mapping where outcrop exposure is poor.

Since publication of Garrett and Nichol's paper, several other studies have been made using factor analysis on stream sediments. Saager and Sinclair (1974) applied Q and R-mode analysis to a survey composed of 158 stream sediments. Their results were similar to those of Garrett and Nichol in that several of the factors appear to be related to geologic processes. Closs and Nichol (1975) applied R-mode factor analysis and regression analysis to stream sediments in the Notre Dame Bay district of Newfoundland. The results of this study supported previous studies and concluded that factor analysis could aid in the interpretation of geochemical data.

Factor analysis has been shown to be useful when applied to determine geochemical processes associated with mineralization (Koo and Mossman, 1975). In this study, factor analysis extracted three associations that were consistent with the known geology of the Flin Flon Cu-Zn deposit located along the Manitoba and Saskatchewan border, Canada. These associations expressed the primary zoning and distributions of the elements in and around the mine.

Recently, a geochemical study involving soils as a sample medium was performed (Tripathi, 1979). This study is one of the few studies where factor analysis has been applied to soils. In this study, factors were found to express several geochemical processes such as mineralization, serpentinization, and adsorption. The above author also suggested that factor analysis could be used routinely in exploration.

Although most studies imply that factor analysis can be an aid in solving geologic problems, this type of data analysis can often lead to erroneous interpretations (Temple, 1978; Trochimczyk and Chayes, 1978). Objections to the method usually point to the subjective nature in which the number of factors are chosen or the manner in which rotation of factors is accomplished. In this study only principal components are used, and in an analysis of this type, rotation is not done and there is no prior knowledge of the number of factors to be used.

DATA ANALYSIS

Tables 3 and 4 show basic statistics for the original data from the Rio Tanama and Rio Vivi districts. Calculations for the mean and standard deviation were computed ignoring any data which had qualified values, and therefore, represents samples which fall within the bounds of the analytical method used. These tables also indicate the type and quantity of qualified data for each of the elements.

Tables 5, 6, 7 and 8 show basic statistics and correlations of the data sets where qualified values have been replaced. Note that the correlation matrices for both districts show few strong correlations between elements. In contrast, Tables 9, 10, 11 and 12 show basic statistics for the logarithmically transformed variables. Correlations between the data after transformation show significant improvement over those of the original data set. This improvement in the correlations along with a more symmetrical-shaped curve of the histograms of these elements supports the assumption that the variables consist of lognormal populations.

Tables 13 and 14 show the output from the principal component analysis. The transformed data were used to perform the analysis based on the improved correlation coefficients. Figures 6 and 7 show graphical presentations of the associations extracted from the data by the analysis.

As stated in the introduction, the loadings indicate how strong an influence an element has on each component. In Table 13, Ni, V, Sc, Cr and Mg have the strongest influence on principal component 1 because they have the largest loadings. Samples with high concentrations for these five elements would show high "scores" for principal component 1. A factor score is obtained by multiplying the standardized concentration of an element by a factor coefficient. The coefficients are calculated by multiplying the principal component loading matrix by the inverse of the correlation matrix (Harman, 1976). To make the discussion of the analysis easier, the principal component loadings are considered to express approximations of the factor coefficients.

The interpretation of the principal component loading matrix is usually straightforward. Within a particular principal component, there are often three groups of loadings: one group of high positive loadings; another of loadings close to zero; and a third of low negative loadings. The elements with high positive loadings have a strong association with the factor, form a group in which

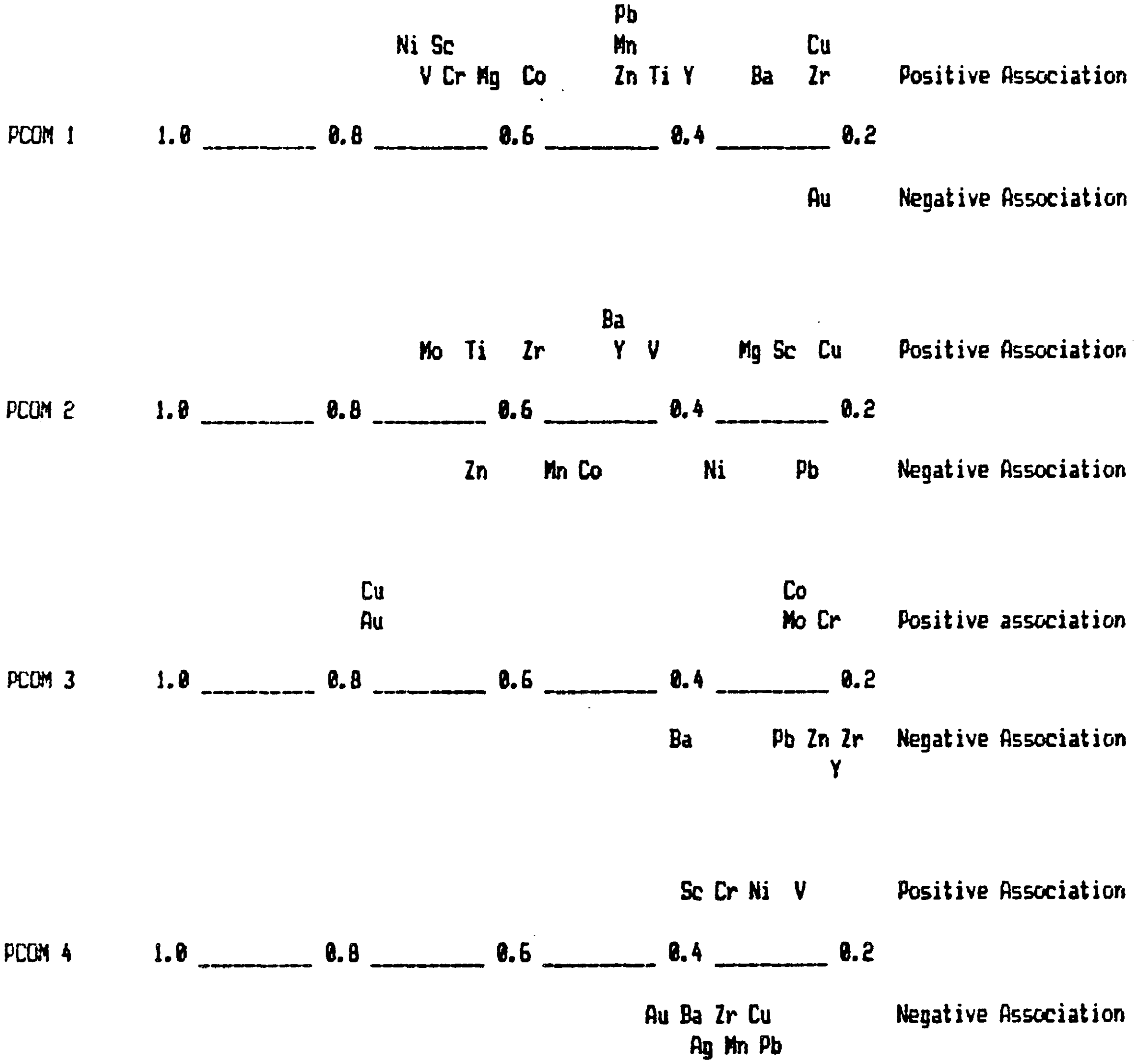

Figure 6. Element loadings in the first four principal components of Rio Tanama

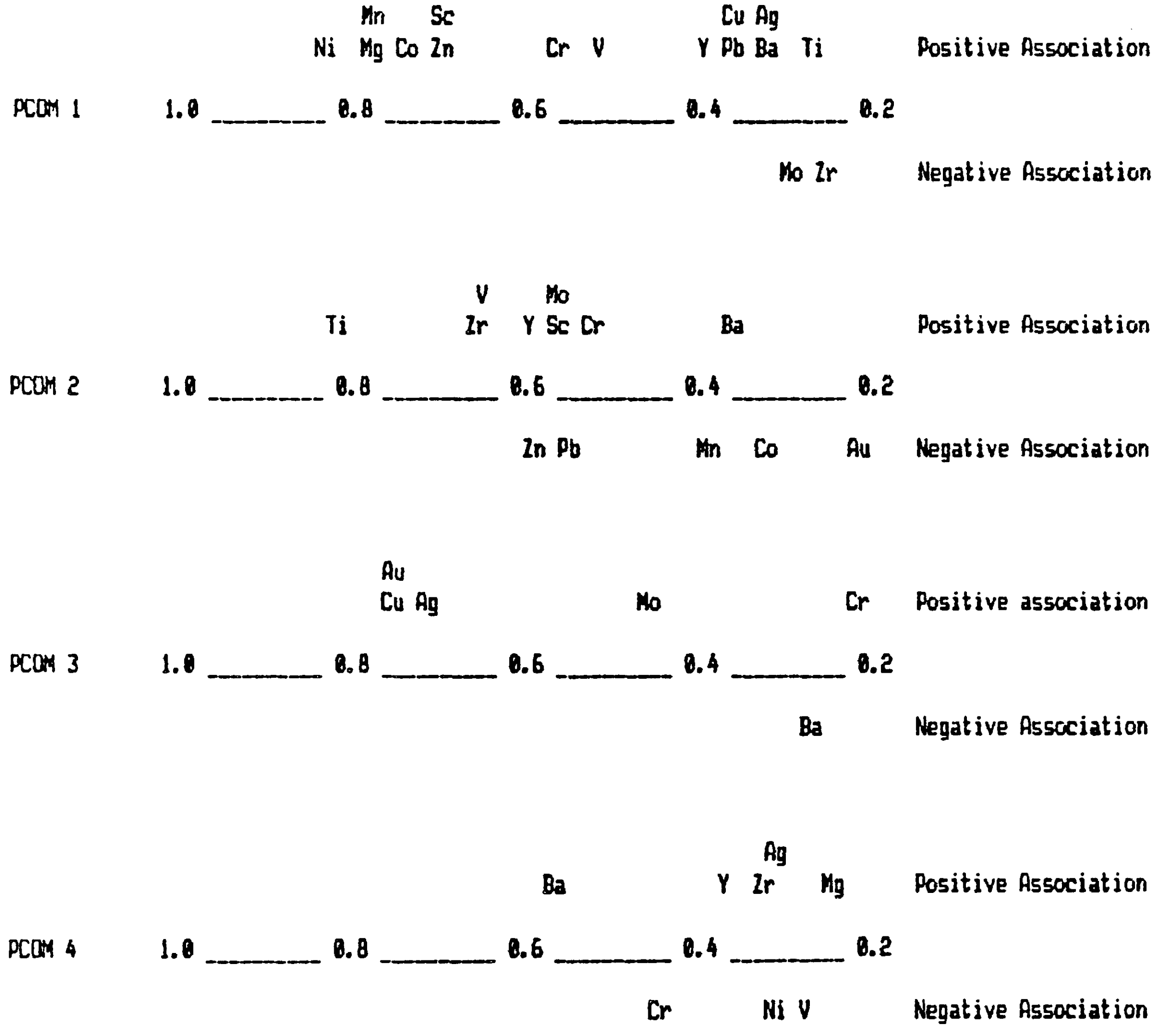

Figure 7. Element loadings in the first four principal components of Rio Vivi

all elements are mutually correlated with each other, and which control the high positive scores of the principal component. Elements with loadings close to zero have little effect on factor scores and little or no association with the factor. The elements with low negative loadings have a strong negative association with the factor, form a group in which all elements are mutually correlated with each other, and which control the low negative scores of the principal component.

The first principal component of Rio Tanama contains one strong positive association composed of all the original elements, excluding Au, Ag and Mo, and accounts for 23.5% of the variance. Principal component 2 accounts for 20.4% of the variance and consists of two associations: the positive association (Mo-Ti-Zr-Ba-Y-V-Mg-Sc-Cu) and the negativve association (Zn-Mn-Co-Ni-Pb). The third principal component accounts for 10% of the variation and consists of two associations: the positive association (Cu-Au-Co-Mo-Cr) and the negative association (Ba-Pb-Zn-Zr-Y).

Associations in Rio Vivi are nearly identical to those of Table 13. Principal component 1 accounts for 28.8% of the variance of all of the original elements. All the elements excluding Au, Mo and Zr are contained in a strong positive association, and Au, Mo and Zr are found in a very weak negative association. Principal component 2 accounts for 21.1% of the variation and is composed of a strong positive association (Ti-V-Zr-Y-Mo-Sc-Cr-Ba) and a strong negative association (Zn-Pb-Mn-Co-Au). Principal component 3 accounts for 10.9% of the variation and consists of a strong positive association (Au-Cu-Ag-Mo-Cr) and a very weak negative association (Ba).

The communalities shown in both tables express the portion of variance being explained by each principal component for each element. The squared value of the multiple correlations indicates how much variance can be explained in an element by correlations with the other elements in the data set. When the communality is greater than the square of the multiple correlations for an element, the variance of that element cannot be explained by associations with other elements. Factor maps have been plotted for both districts and are shown in the following pages. Single element maps are found for both areas in Appendix A.

DISCUSSION OF RESULTS

The discussion of the Rio Tanama deposits was limited by the lack of geological information and the poor quality of the geologic maps of the area. This lack of information required that the study be centered around the Rio Vivi deposits, which have been mapped and are shown in Figure 8, and comparisons extrapolated to the Rio Tanama deposits.

Six factor maps have been plotted for both districts which represent suites of elements that are mutually correlated with each other. Each factor was split into a positive association and a negative association and plotted on separate maps to make the dicussions less complicated.

Figure 9 shows the distribution of factor 1 positive in the Rio Vivi District. This is a suite of elements that is typical of "mafic" minerals and probably represents the distribution of these minerals in the area. Supporting this theory is the close association of high factor score with the basaltic member of the Robles Formation. Conversely, factor 1 negative, Figure 10, is composed of a suite of elements typical of rocks of intermediate to felsic nature. This association is found near many of the quartz, diorite intrusives, and andesitic flows and tuffs in the area.

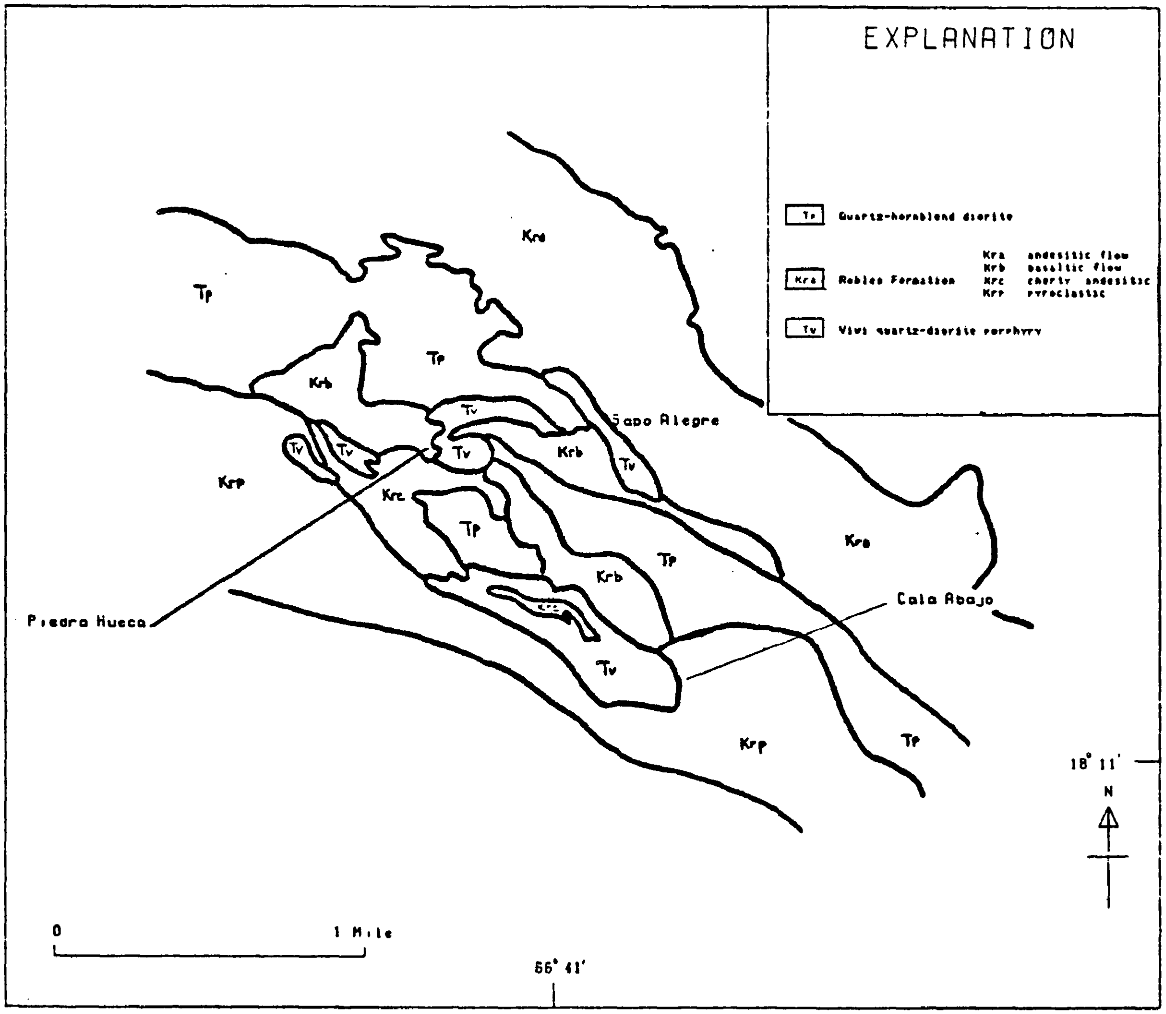

Figure 8. Geology of Rio Vivi deposits - Geology from Barabas

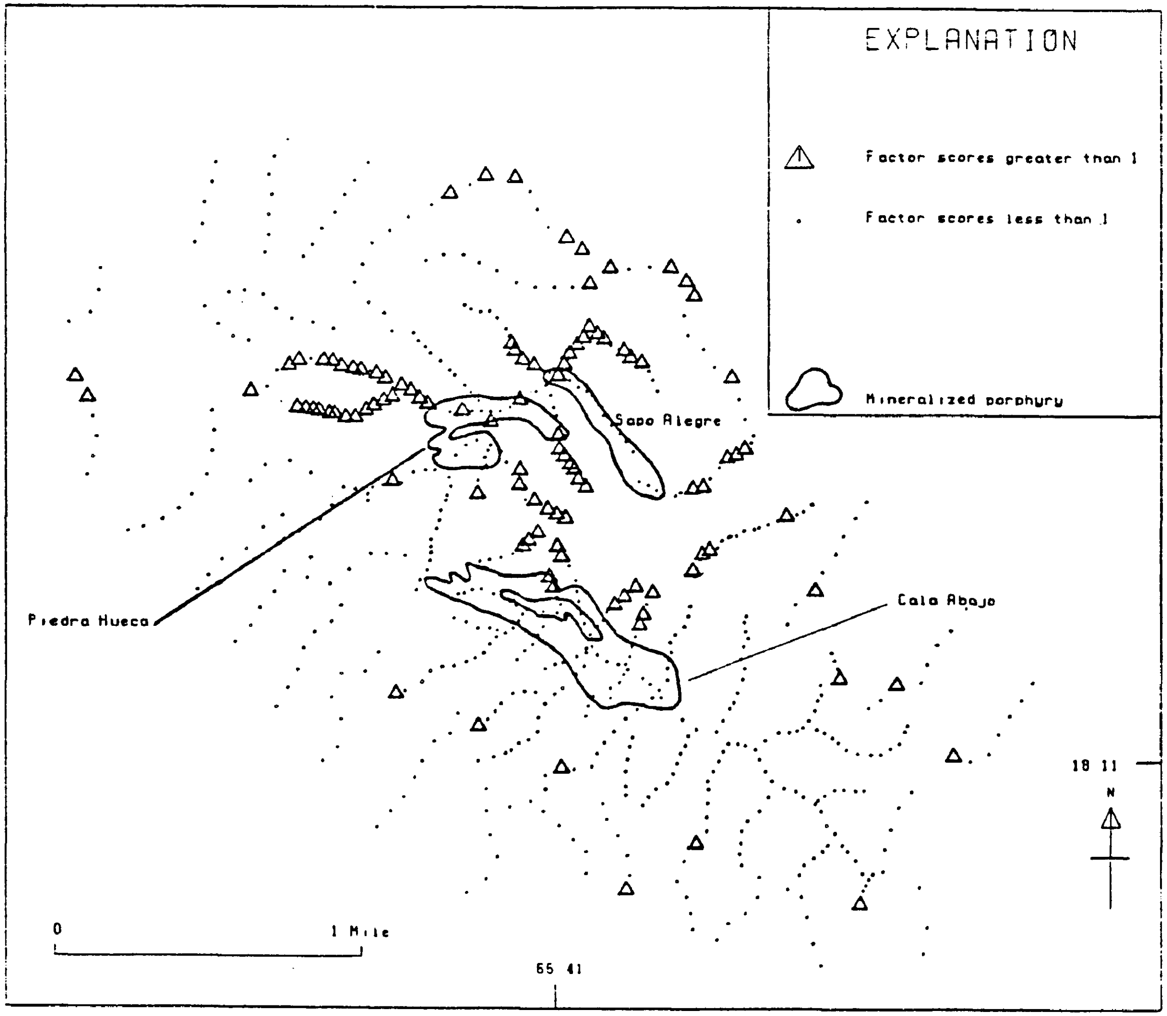

Figure 9. Distribution of factor 1 positive in soil - Rio Vivi

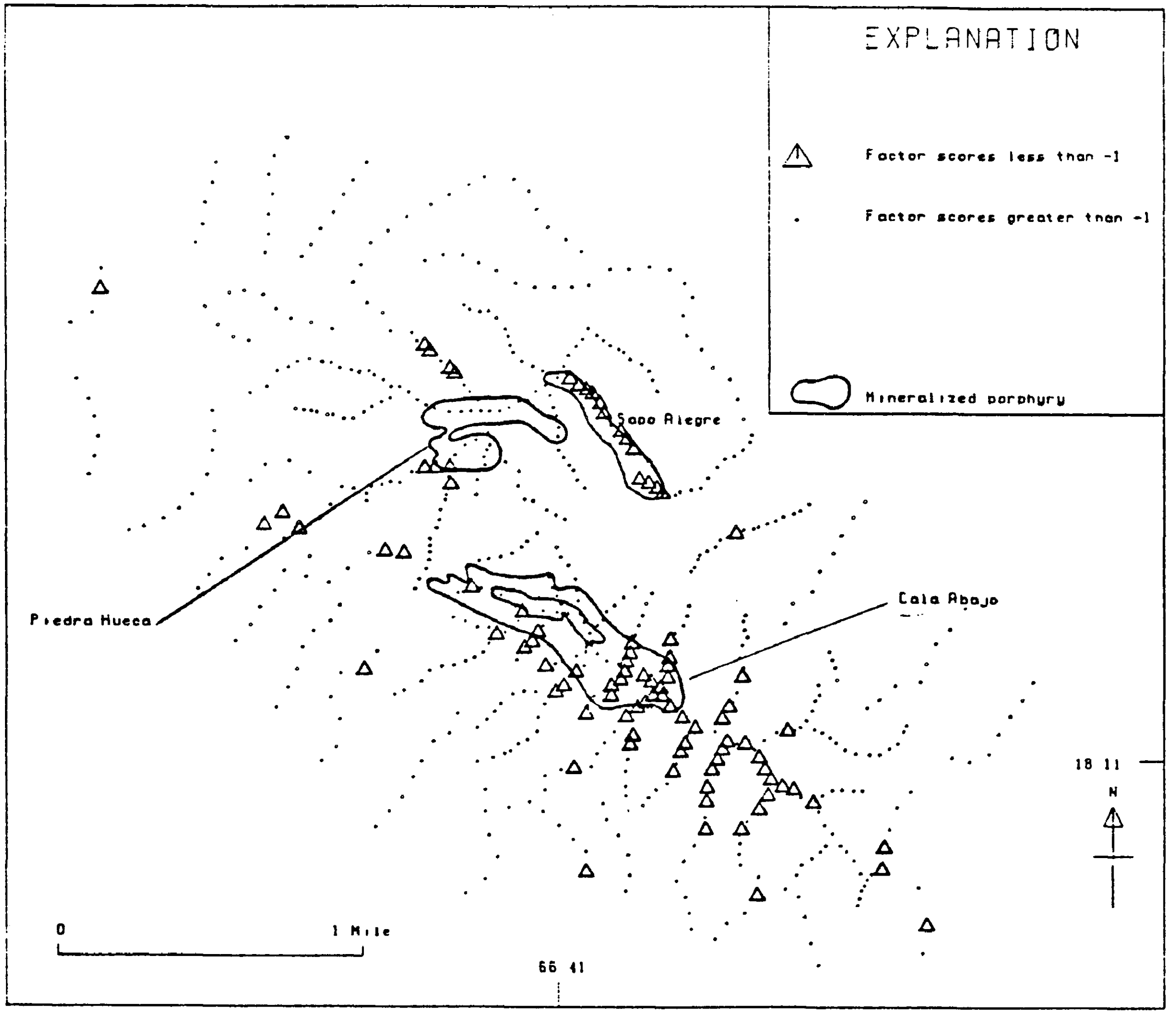

Figure 10. Distribution of factor 1 negative in soil - Rio Vivi

The same situation appears to occur in the Tanama District although an accurate geologic map does not exist. The deposits seem to be surrounded by a "mafic" group of minerals as shown in Figure 11. The suite of elements are nearly identical to those found at Rio Vivi for factor 1 positive. The map of factor 1 negative, Figure 12, differs from the Rio Vivi association in that it is composed of very low scores of gold. This map is nearly identical to the map for gold and provides little explanation for the causes of its distribution except that the gold is associated with the more felsic rocks in the area.

The factor map for principal component 2 positive and negative begins to show the effects of mineralization in the area. In Figure 13 the distribution of factor 2 positive shows a strong correlation with the mineralized areas in the Rio Vivi region. This suite is associated with minerals deposited close to the center of mineralization and is very resistant to secondary processes of transportation. From the distribution of this suite in Figure 13, it can be seen that the scores enclose an area that contain all three deposits.

Perhaps more striking is the distribution of factor 2 negative association. This distribution is composed of elements that occur in minerals that form halos around

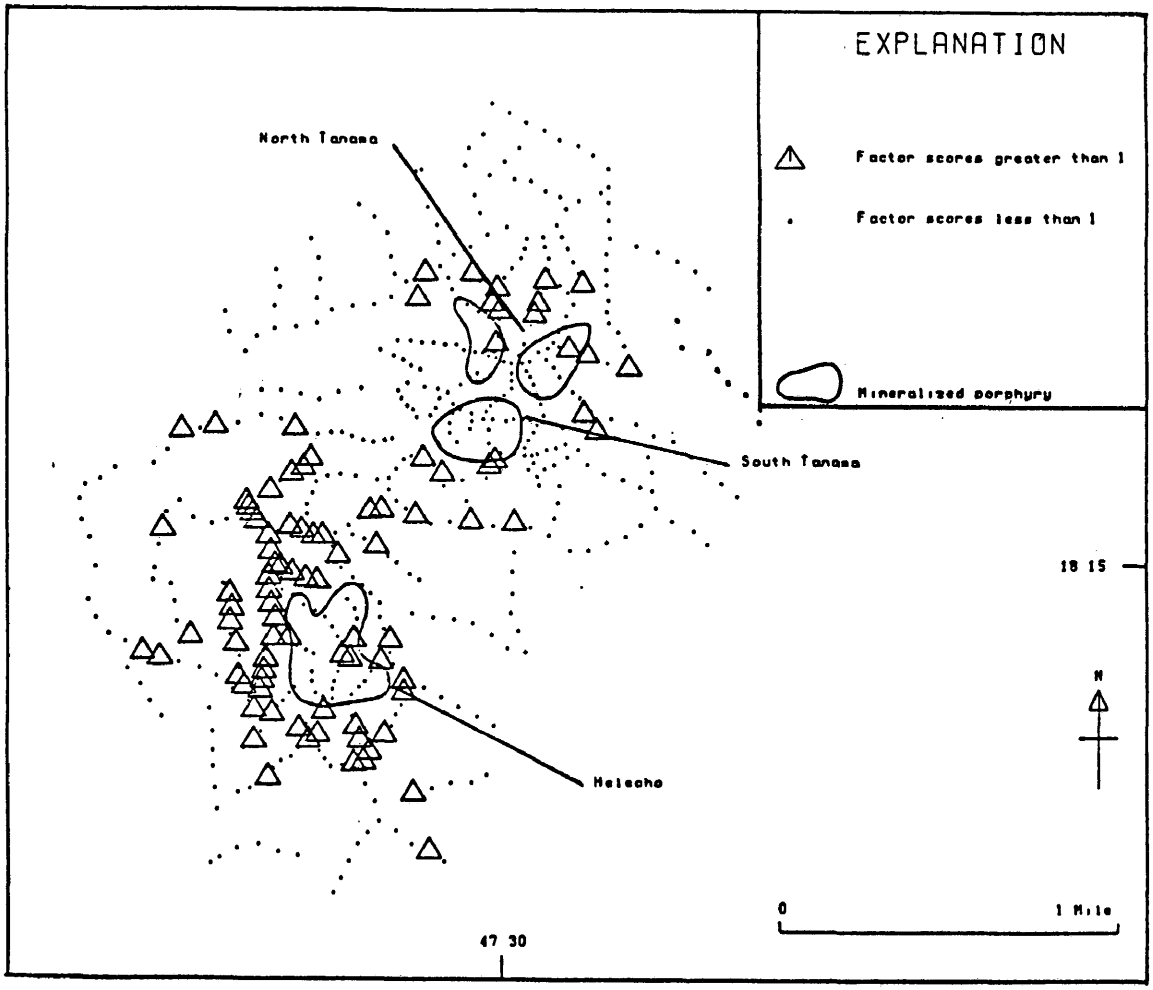

Figure 11. Distribution of factor 1 positive in soil - Rio Tanama

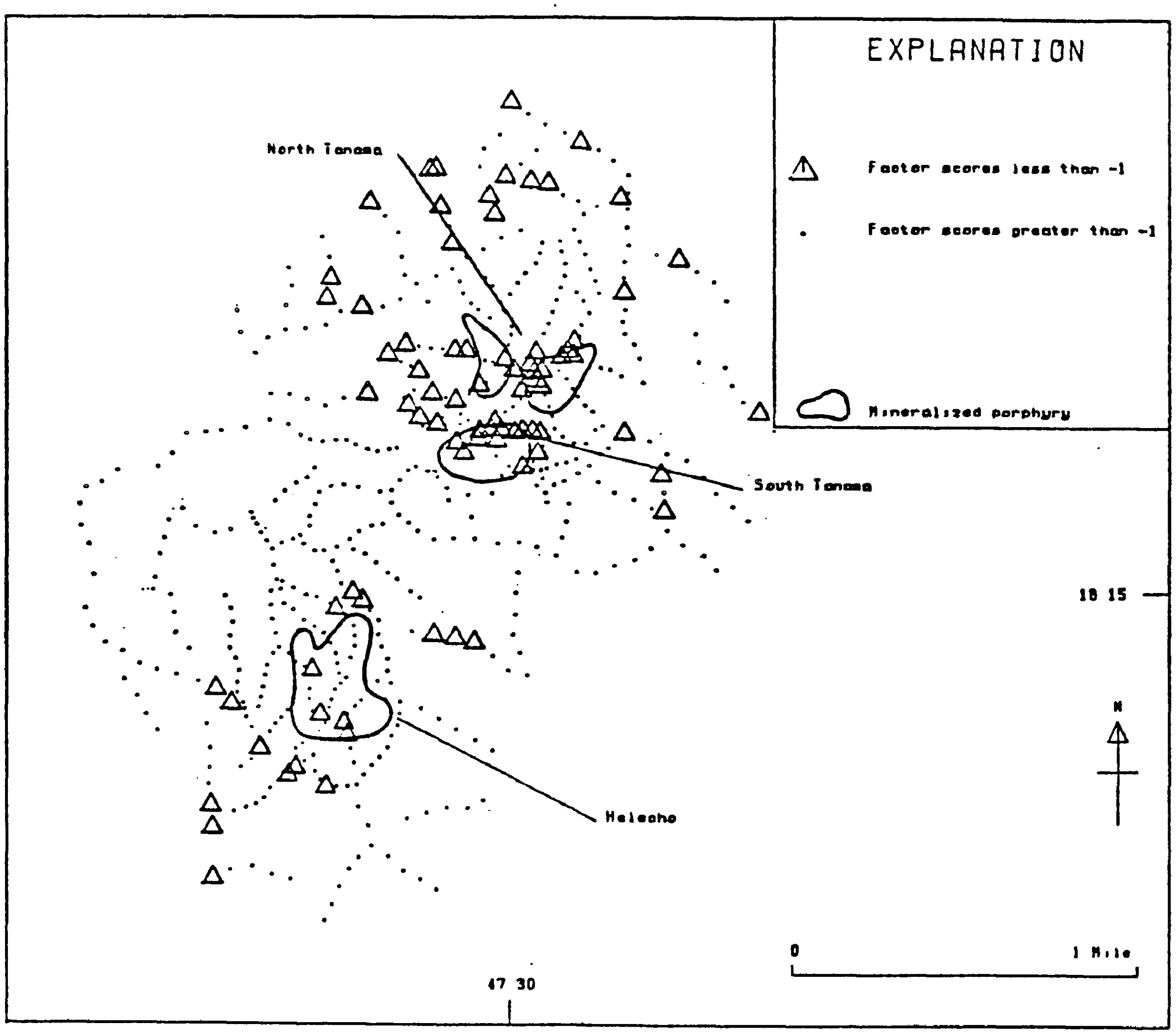

Figure 12. Distribution of factor 1 negative in soil - Rio Tanama

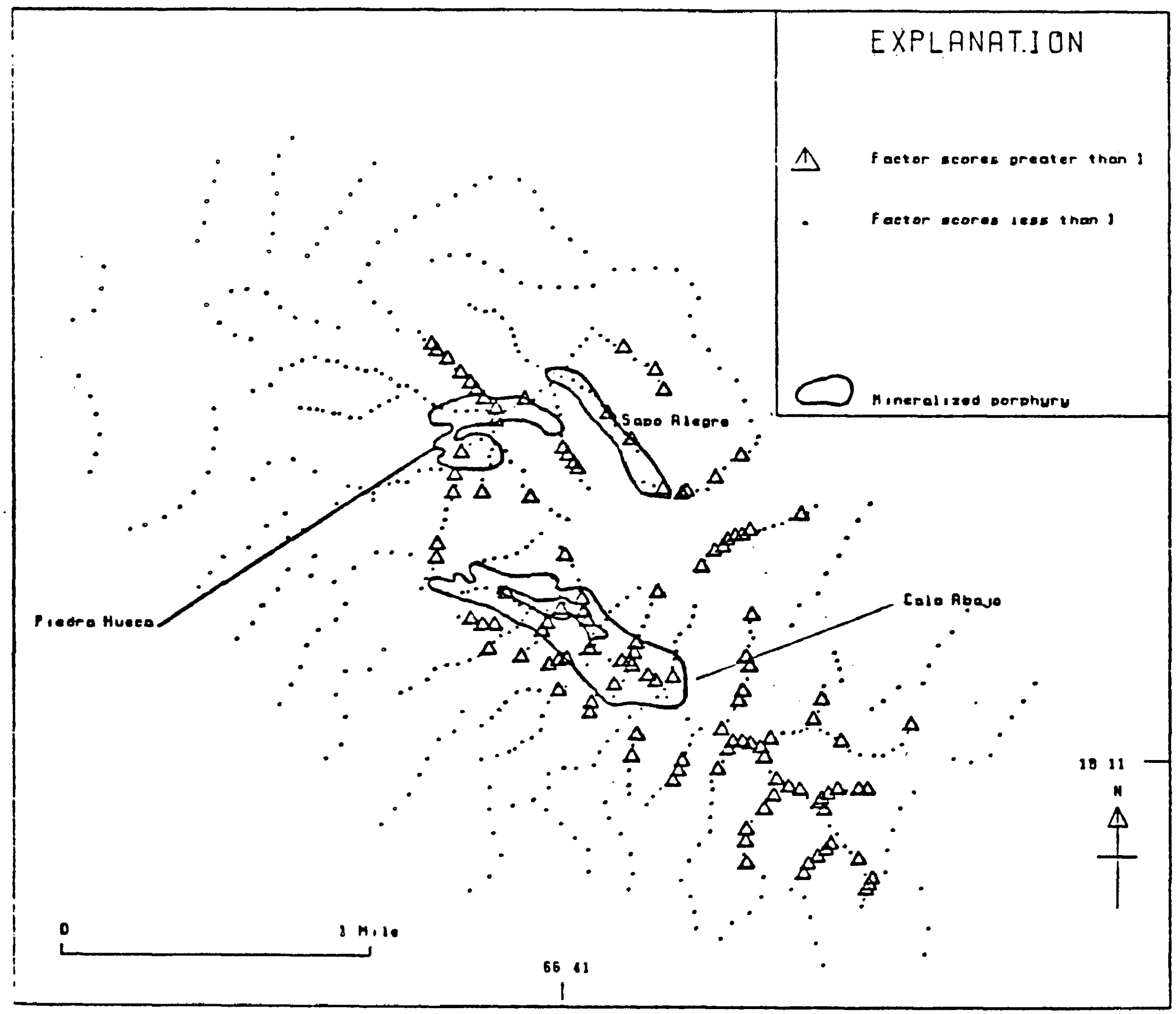

Figure 13. Distribution of factor 2 positive in soil - Rio Vivi

typical porphyry copper deposits. These minerals are also quite mobile in the secondary environment, and for these reasons, Figure 14 probably represents a combination of primary and secondary processes that concentrated these minerals around the deposits. It is obvious from the map that the sampling procedure never extended past the influence of mineralization, but unpublished stream sediment surveys indicate that the group of elements associated with factor 2 negative decreases to background levels just beyond the boundaries of the map and therefore provide a doughnut-like pattern around the deposit that is approximately 6 miles across.

In terms of regional exploration, the advantages of seeking a target 6 miles across as compared to that of a target 1/2 mile across (which is the size of the largest deposit known on the island) is obvious. The distribution shown in Figure 12 provides a very effective means of locating possible economic regions. This distribution is similar to those of the single element maps for Pb, Zn, Mn, Co (see appendix), but none of these maps provide the striking detail of the factor map.

The same conclusion as referenced previously in this thesis for factor 2 in the Rio Vivi district can be made for Rio Tanama. The suite of elements for the positive and

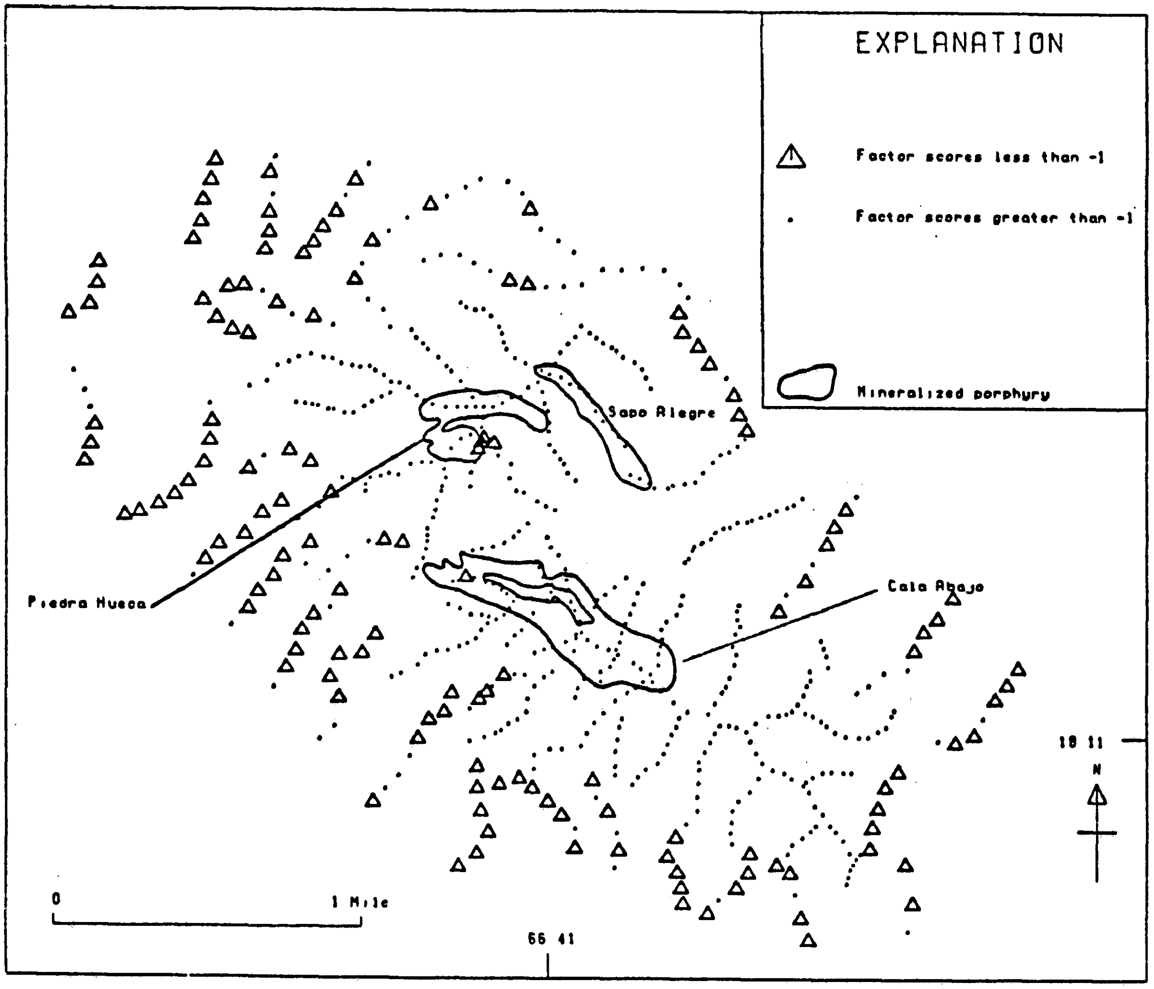

Figure 14. Distribution of factor 2 negative in soil - Rio Vivi

negative portions of the factor are nearly identical. This is supported by identical distributions around the deposits of both districts shown in Figures 15 and 16 for the Rio Tanama District of the "halo suite" of elements Zn, Pb, Mn and Co. The distribution is particularly good at the Rio Tanama District.

The last important factor for the Rio Vivi area, factor 3, is shown in Figures 17 and 18. The spatial distribution of the positive portion of the factor corresponds to all the areas of localized mineralization in the district. This map shows the extent to which factor analysis can delineate deposits in environments similar to that found in Puerto Rico. Nearly all the high values of factor 3 positive occur directly over mineralized rock and provide a good indication of where core drilling for assays should be located.

The distribution of factor 3 negative is hard to explain geologically except that many of the elements found in this suite are distributed around the perimeter of mineralization similar to the suite of elements found in factor 2 negative. The map of this factor (Figure 18) shows a similar pattern to that found in Figure 14 and is probably related to a similar process.

The distribution of factor 3 in the Rio Tanama District was again nearly identical to that of the Rio Vivi and is

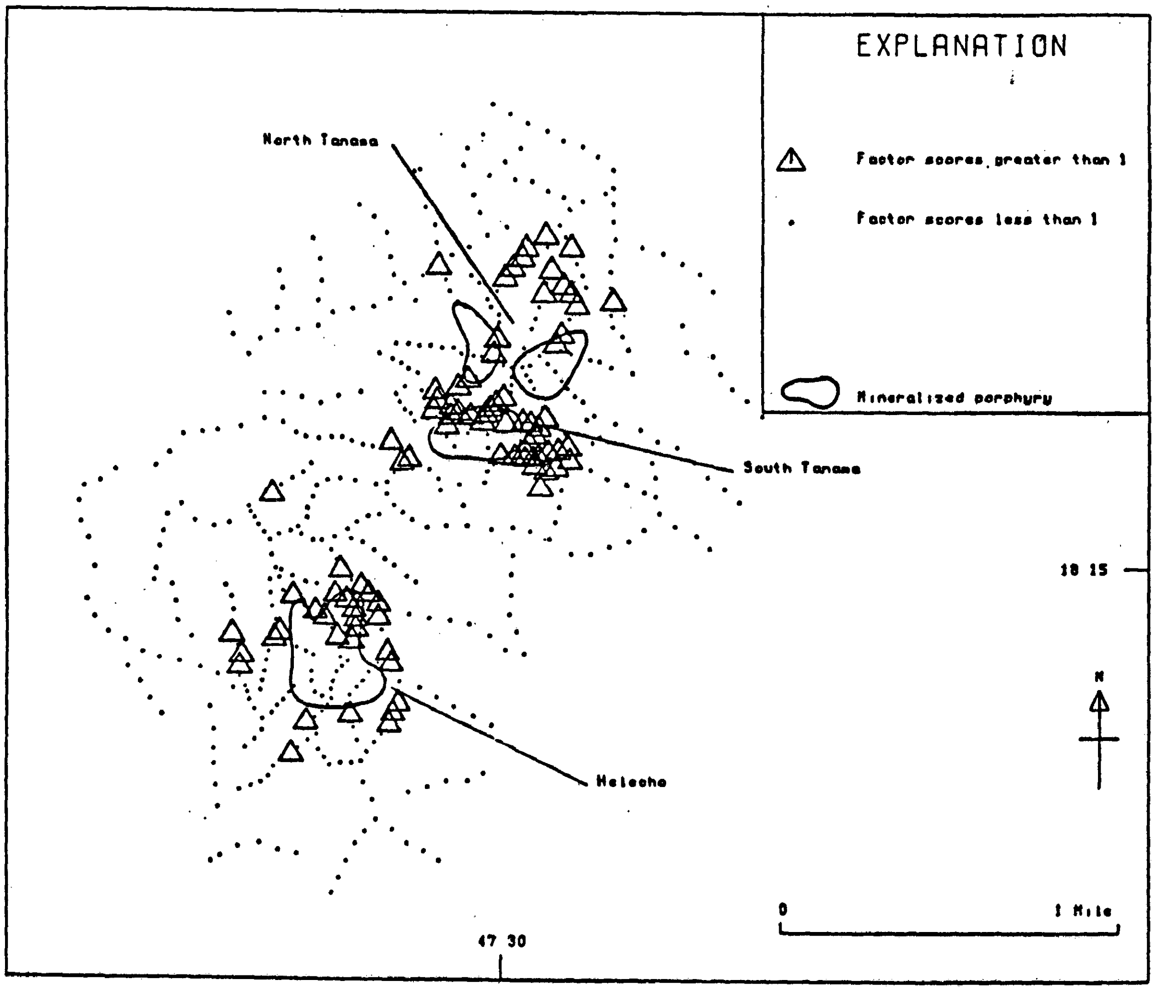

Figure 15. Distribution of factor 2 positive in soil - Rio Tanama

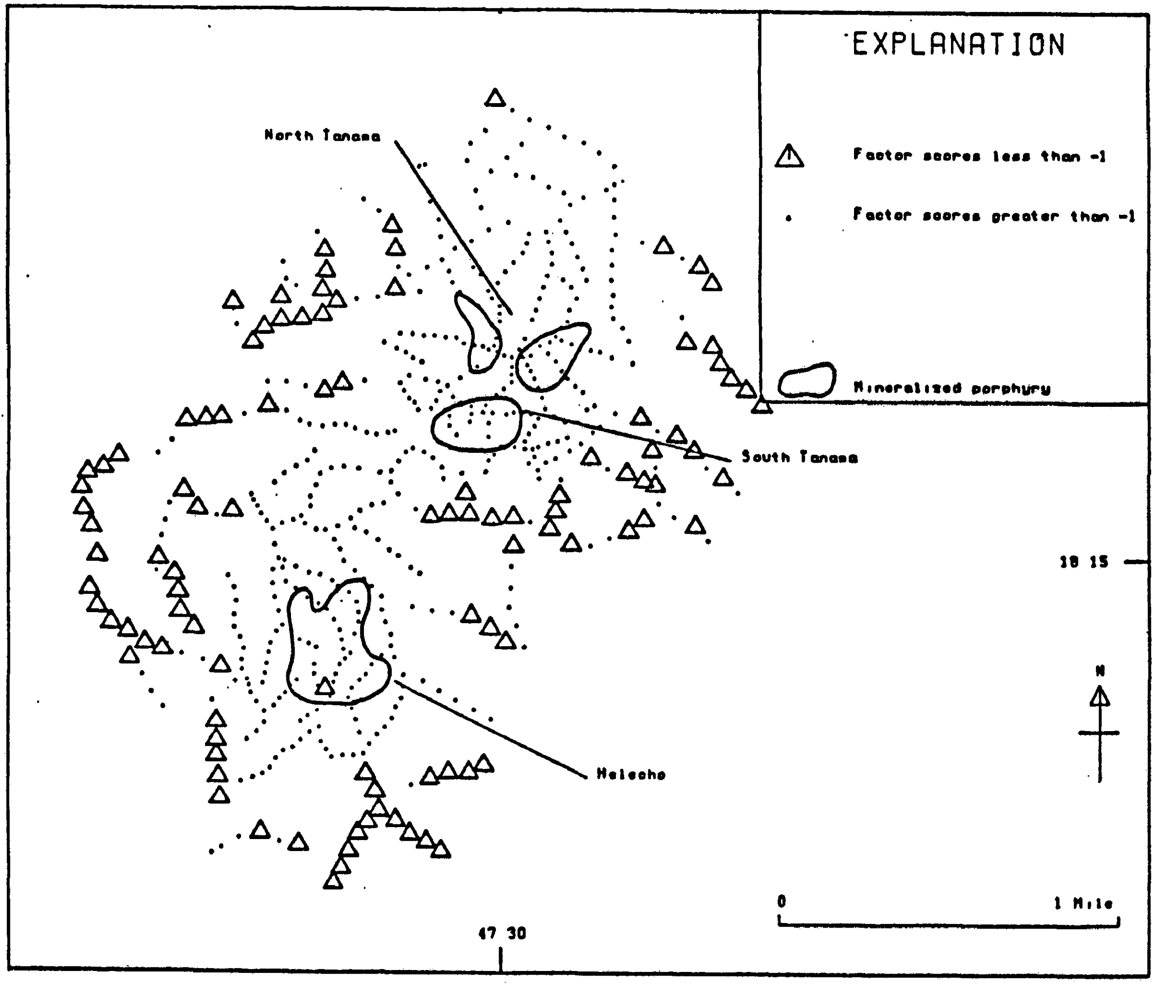

Figure 16. Distribution of factor 2 negative in soil - Rio Tanama

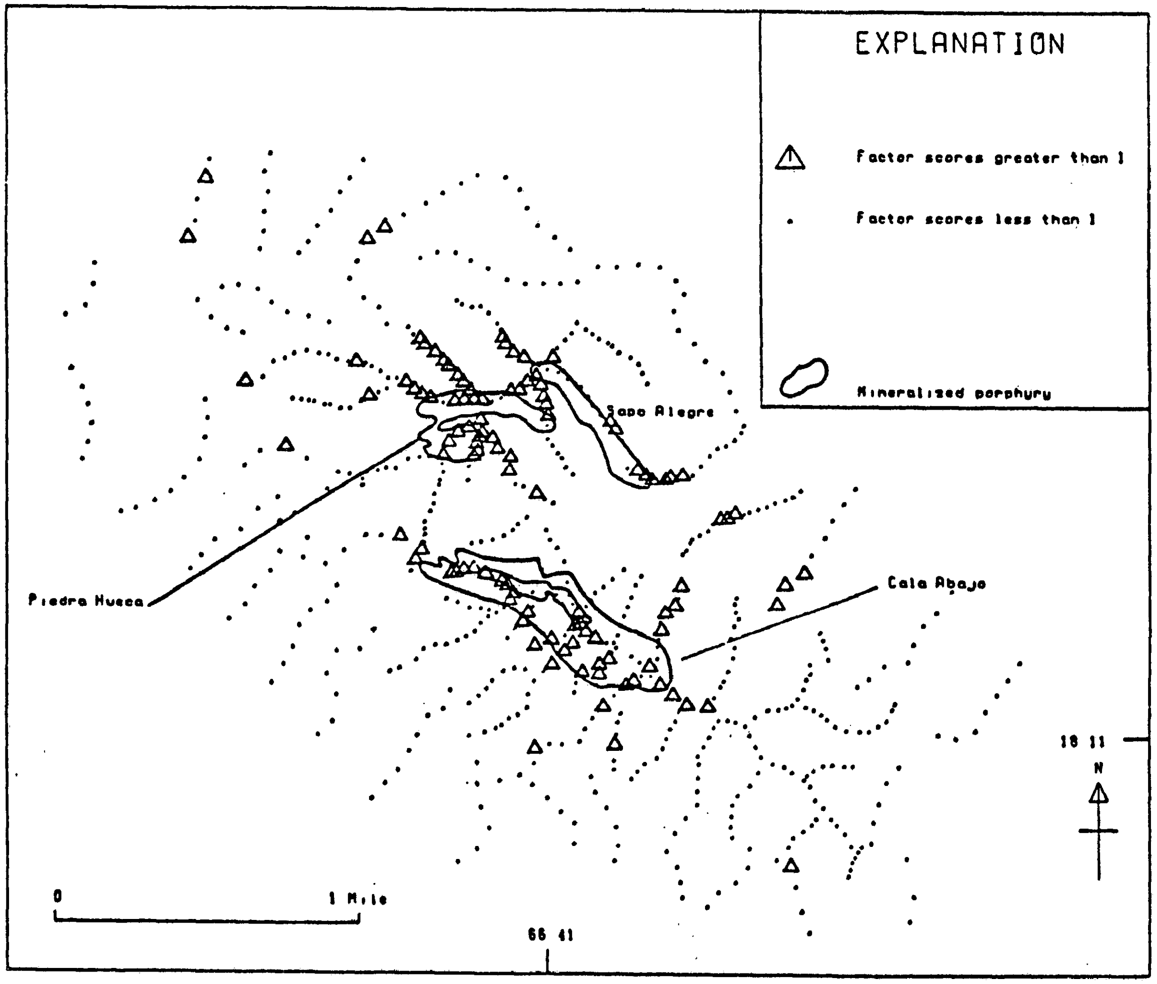

Figure 17. Distribution of factor 3 positive in soil - Rio Vivi

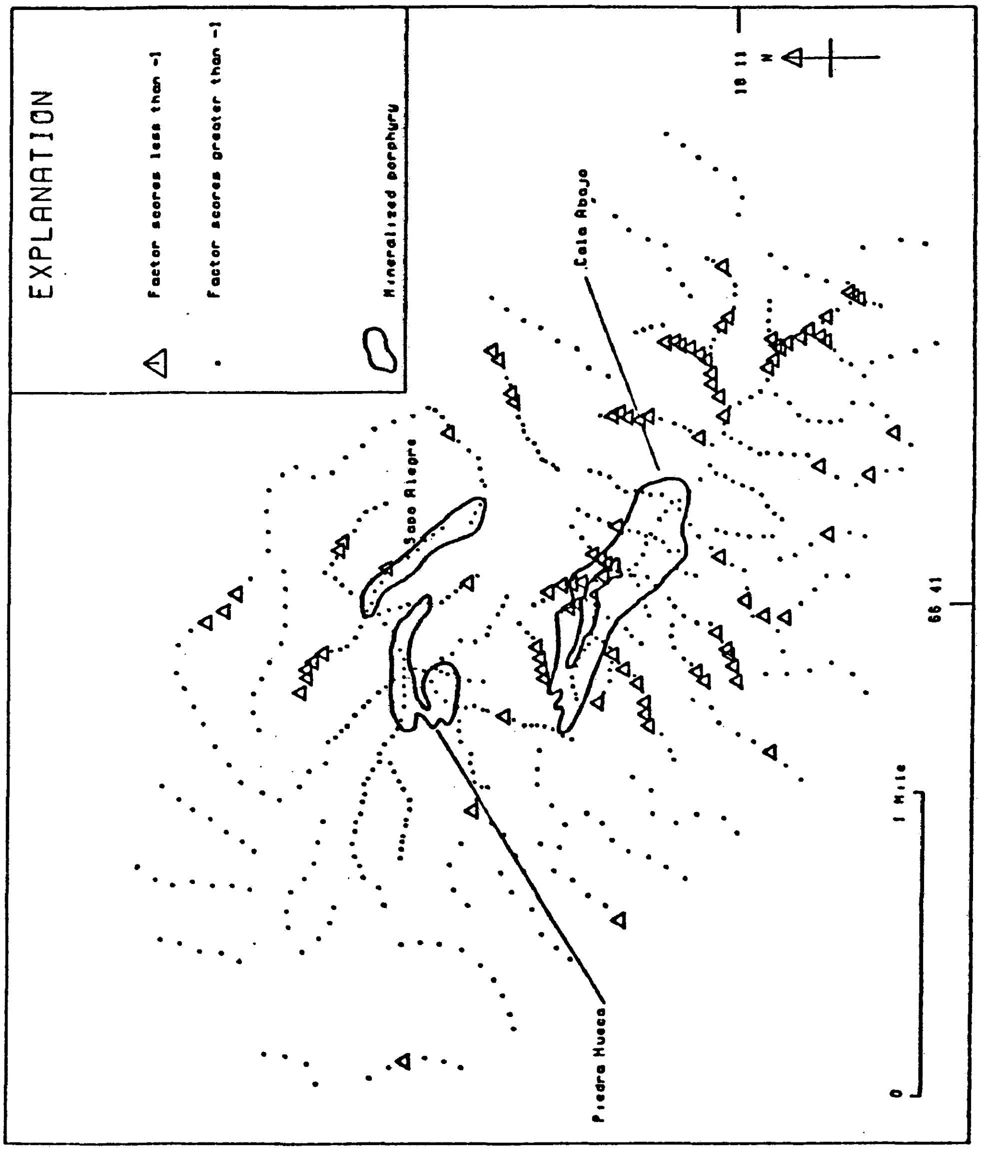

Figure 18. Distribution of factor 3 negative in soil - Rio Vivi

shown in Figures 19 and 20. The suite of elements associated with factor 3 positive is identical for both districts with the exception of silver in the Rio Tanama District. The spatial distribution of the positive portion forms a dense pattern around all the deposits making recognition of mineralized areas extremely easy.

The negative portion of the factor was similar to the Rio Vivi District in that geological explanation was difficult. The pattern did show a tendency to surround the known deposits and again was composed of elements that are typically found in halos surrounding mineralization.

The single element maps for both districts are provided in the appendix so that the reader can compare the two methods using his own knowledge of geochemistry. It is the belief of this author that no two single element maps can be found that provide the same information that the factor 2 negative and factor 3 positive maps provide, and no easier method is available to date of combining any of the single element maps to provide as good an indication of mineralization as that of the factor maps.

CONCLUSIONS

The previous discussion of results shows the value of factor analysis as an exploration technique in deposits similar to that found in the Rio Vivi and Rio Tanama deposits of Puerto Rico. The method provides the geologist with essentially all the information that can be extracted from the data. It also forces the study of suites of elements acting as a group, which is the way deposits are formed, instead of concentrating on one or two single elements which may have distributions composed of several processes other than that of mineralization. In the two separate districts the results of the factor analysis were strikingly similar, implying similar methods of mineralization and fulfilling the basic requirement of consistent results within an area.

Based upon the results, factor analysis enables the use of a regional sampling pattern that has spacing of greater than that used in the original survey, possibly one sample every half mile to effectively delineate the halos around the deposits that were expressed in Figures 12 and 18. If factor analysis is utilized, for example, 100 to 150 samples could be taken in order to first expose target areas where more intensive sampling could then be established. Within these target areas, an additional 100 to 150 samples could then define the actual drilling targets. Therefore, the same information that was derived from the 500 to 600 samples of the original survey could be obtained from only 200 to 300 samples if factor analysis were used. The majority of costs that occur in an exploration program come from the collection and analyzing of samples, it is evident that this cost could be substantially reduced by the application of proper sampling techniques followed by factor analysis.

The additional costs of running factor analysis on a data set should also be addressed in this section. Since nearly all exploration geologists use some method of statistical analysis, it is assumed that the costs of obtaining a data set that has been checked and is free of errors are standard within a particular company and that the computer analysis of these data is a routine procedure. The costs of going from a clean data set of 500 to 600 samples analyzed for 19 elements to the results of the factor analysis method used in this thesis were under $100.00. The cost, when compared to the additional information and possible exploration cost savings, seems quite small.

With the advancement of analytical techniques such as plasma spectroscopy, which can provide information on twenty to thirty elements at approximately the same accuracy and cost as one element by atomic absorption, the ability of factor analysis to reduce data into a small number of variables becomes even more important. The geologist faced with the 10,000 to 15,000 pieces of information possible from a small survey of 500 sample locations could easily miss all but the most obvious associations. It is these types of applications where factor analysis will be most beneficial and prove to be invaluable in mineral exploration programs.

REFERENCES CITED

Barabas, A.H. 1977 "Petrologic and Geochemical Investigations of Porphyry Copper Mineralization in West Central Puerto Rico" Ph.D. Thesis, Yale University.

Bradley, R.A. 1971 "The Geology of the Rio Vivi Porphyry Copper Deposits, Puerto Rico" Geological Society of America Abstracts, p. 551.

Chapman, R.P. 1978 "Evaluation of Some Statistical Methods of Interpreting Multi-ELement Geochemical Drainage Data from New Brunswick" Mathematical Geology, V. 10, p. 195-224.

Closs, L.G. and Nichol, I. 1975 "The Role of Factor and Regression Analysis in the Interpretation of Geochemical Reconnaissance Data" Canadian Journal of Earth Science, 12, p. 1316-1330.

Cox, D.P., Larson, R.R., Tripp, R.B. 1973 "Hydrothermal Alteration in Puerto Rican Porphyry Copper Deposits" Economic Geology, V. 68, No. 8, p. 1329-1334.

Cox, D.P., Gonzalez, J.P., and Nash, T.J. 1975 "Geology, Geochemistry, and Fluid-Inclusion Petrography of the Sapo Alegre Porphyry Prospect and Its Metavolcanic Wallrocks, West Central Puerto Rico" Journal of Research, U.S. Geological Survey, V. 3, p. 313-327.

Davis, J.C. 1973 "Statistics and Data Analysis in Geology" John Wiley and Sons, Inc., New York.

Garrett, R.G. and Nichol, I. 1969 "Factor Analysis as an Aid in the Interpretation of Regional Geochemical Stream Sediment Data" Exploration Geochemistry Symposium, Colorado School of Mines Quarterly, 1969, p. 243-264.

Grimes, D.J. and Marranzino, A.P. 1968 "Direct-current Arc and Alternating-current Spark Emission Spectrographic Field Methods for the Semiquantitative Analysis of Geologic Materials" Circular of the U.S. Geological Survey, No. 591, p. 6.

Harmon, H.H. 1976 "Modern Factor Analysis" University of Chicago Press, Chicago.

Koch, G.S., Jr. and Link, R.F. 1971 "Statistical Analysis of Geochemical Data" V. 1 and 2, John Wiley and Sons, Inc., New York.

Koo, J. and Mossman, D.J. 1975 "Evolution of Primary and Secondary Geological Processes at the Flin Flon Cu-Zn Deposit, Manitoba and Saskatchewan, Canada, Using Factor-Vector Analysis of Ore Geochemistry" Chemical Geology, V. 16, p. 1-14.

Krumbein, W.C. and Greybill, F.A. 1963 "An Introduction to Statistical Models in Geology" McGraw-Hill Book Co., New York.

Levinson, A.A. 1974 "Introduction to Exploration Geochemistry" Applied Publishing Ltd., Calgary, Alberta, Canada.

Learned, R.W. and Boissen, R. 1973 "Gold - A Useful Pathfinder Element in the Search for Porphyry Copper Deposits in Puerto Rico" Geochemical Exploration 1972, Institute of Mining and Metallurgy, London, p. 93-103.

Lutjen, G.P. 1971 "The Curious Case of the Puerto Rican Copper Mines" Engineering and Mining Journal, V. 172, p. 74-84.

Nichol, I. 1969 "The Role of Some Statistical and Mathematical Methods in the Interpretation of Regional Geochemical Data" Economic Geology, V. 64, p. 204-220.

Nichol, I. 1973 "The Role of Computerized Data Systems in Geochemical Exploration" C.I.M. Bull., V. 66, p. 59-68.

Rose, A.W. 1972 "Statistical Interpretation Techniques in Geochemical Exploration" Transactions of the American Institute of Mining and Metallurgical Engineers, V. 252, p. 233-239.

Rummel, R.J. 1970 "Applied Factor Analysis" Northwestern University Press, Evanston.

Saager, R. and Sinclair, A.J. 1974 "Factor Analysis of Stream Sediment Data from the Mount Nansen Area, Yukon Territory, Canada" Mineral Deposits, V. 9, p. 243-252.

Temple, J.C. 1978 "The Use of Factor Analysis in Geology" Mathematical Geology, V. 10, p. 379-387.

Thompson, C.E., Nakogawa, H.M. and Van Sickle, G.H. 1968 "Rapid Analysis for Gold in Geologic Materials" U.S. Geological Society Bulletin 600-B, p. 130-132.

Tripathi, V.S. 1979 "Factor Analysis in Geochemical Exploration" Exploration Geochemitry, V. 11, p. 263-276.

Trochimczyk, J. and Chayes, F. 1978 "Some Properties of Principal Component Scores" Mathematical Geology, V. 10, p. 43-52.

Ward, F.N. et al. 1969 "Atomic Absorption Methods of Analysis Useful in Geochemical Exploration" U.S. Geological Survey Bulletin 1289, 45 p.

APPENDIX

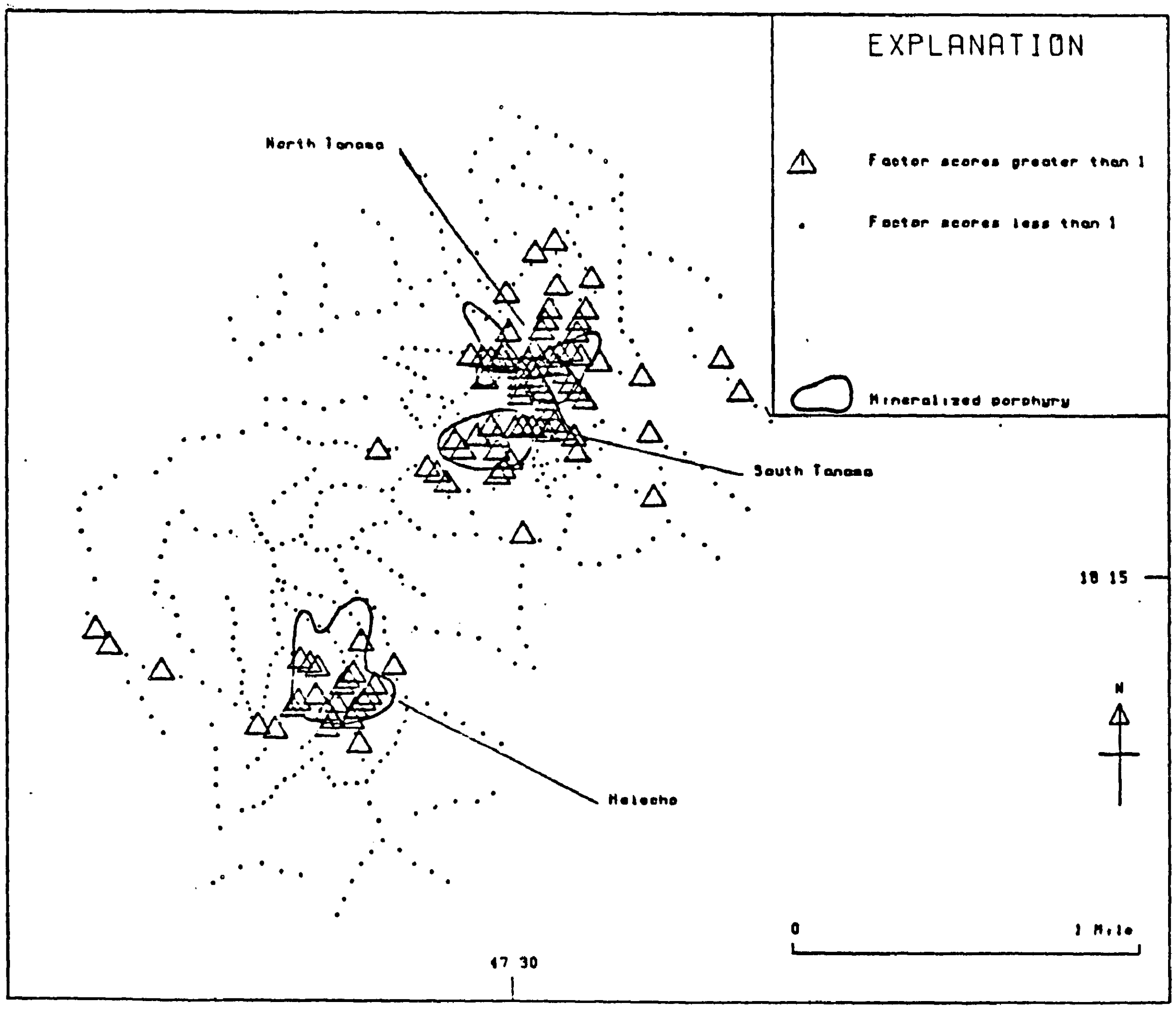

Figure 19. Distribution of factor 3 positive in soil - Rio Tanama

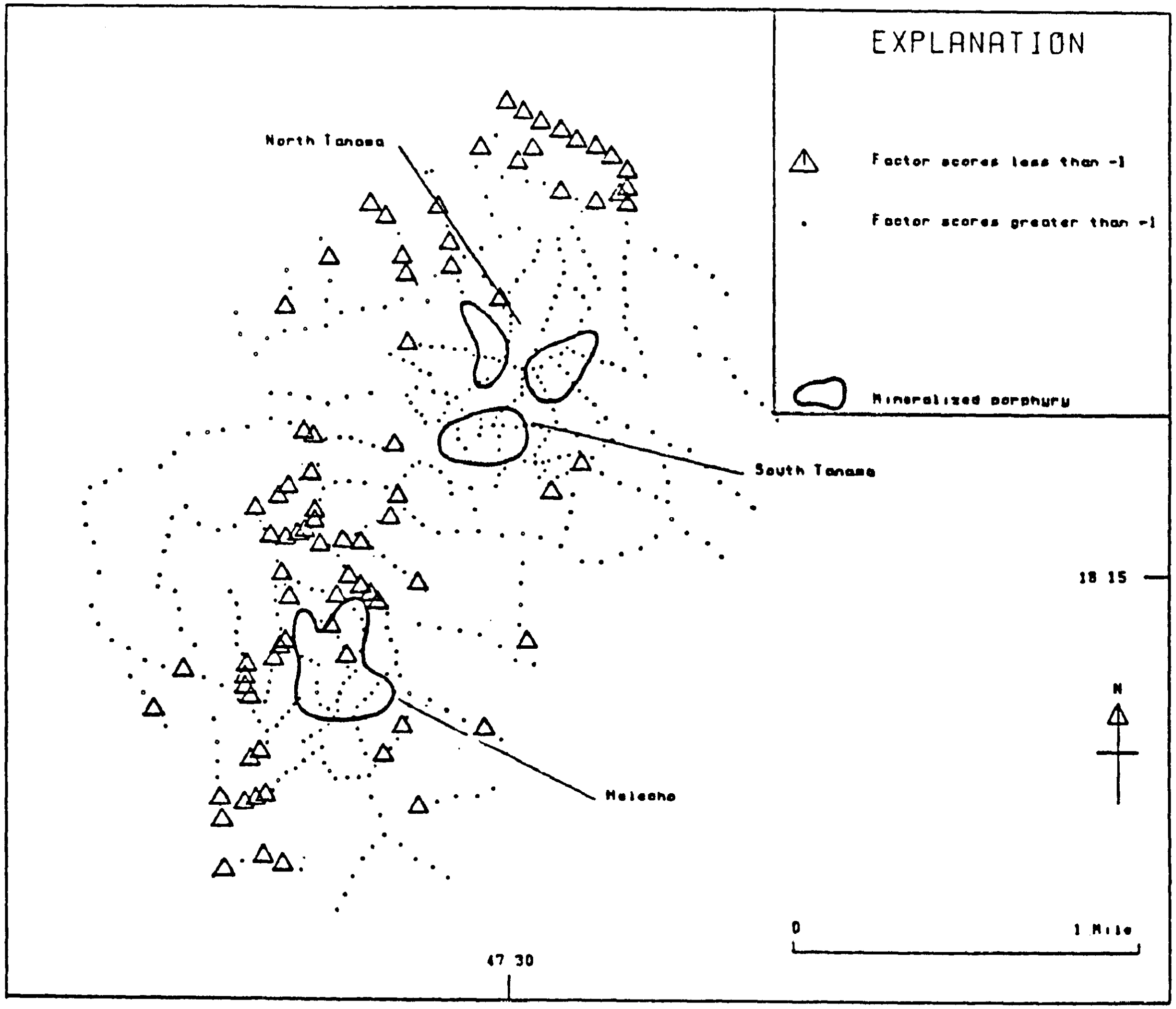

Figure 20. Distribution of factor 3 negative in soil - Rio Tanama

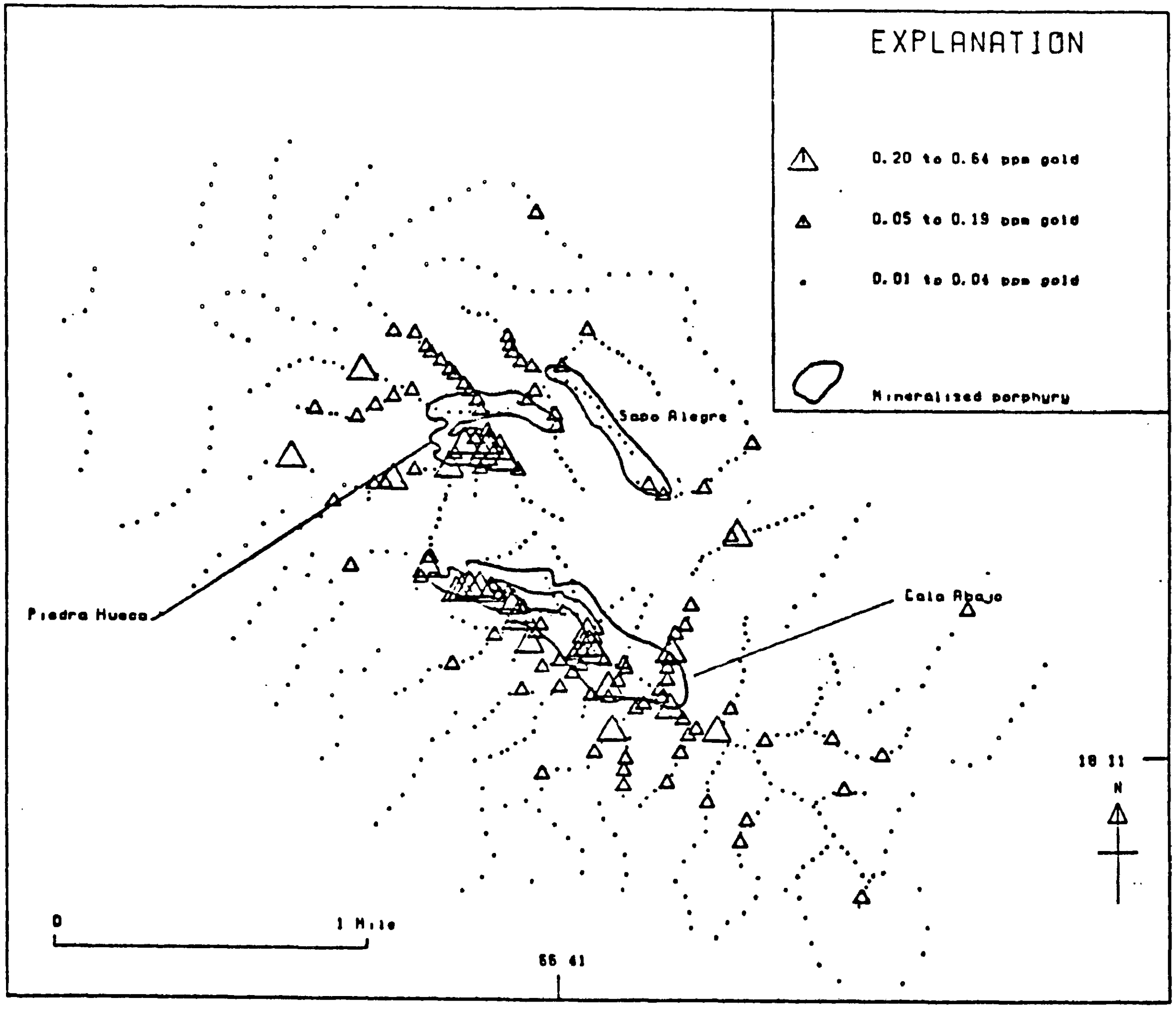

Figure 21. Distribution of gold in soil - Rio Vivi

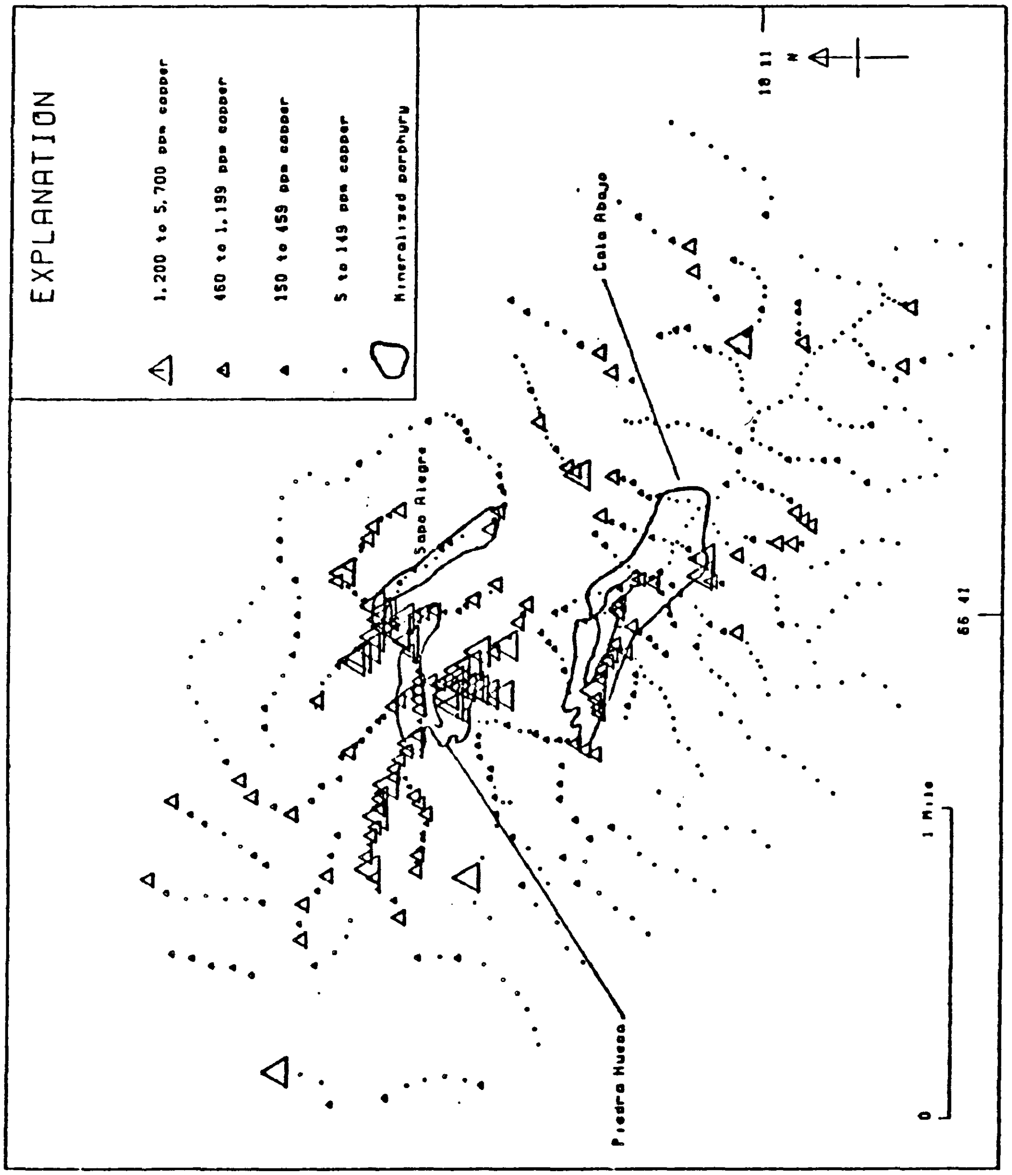

Figure 22. Distribution of copper in soil - Rio Vivi

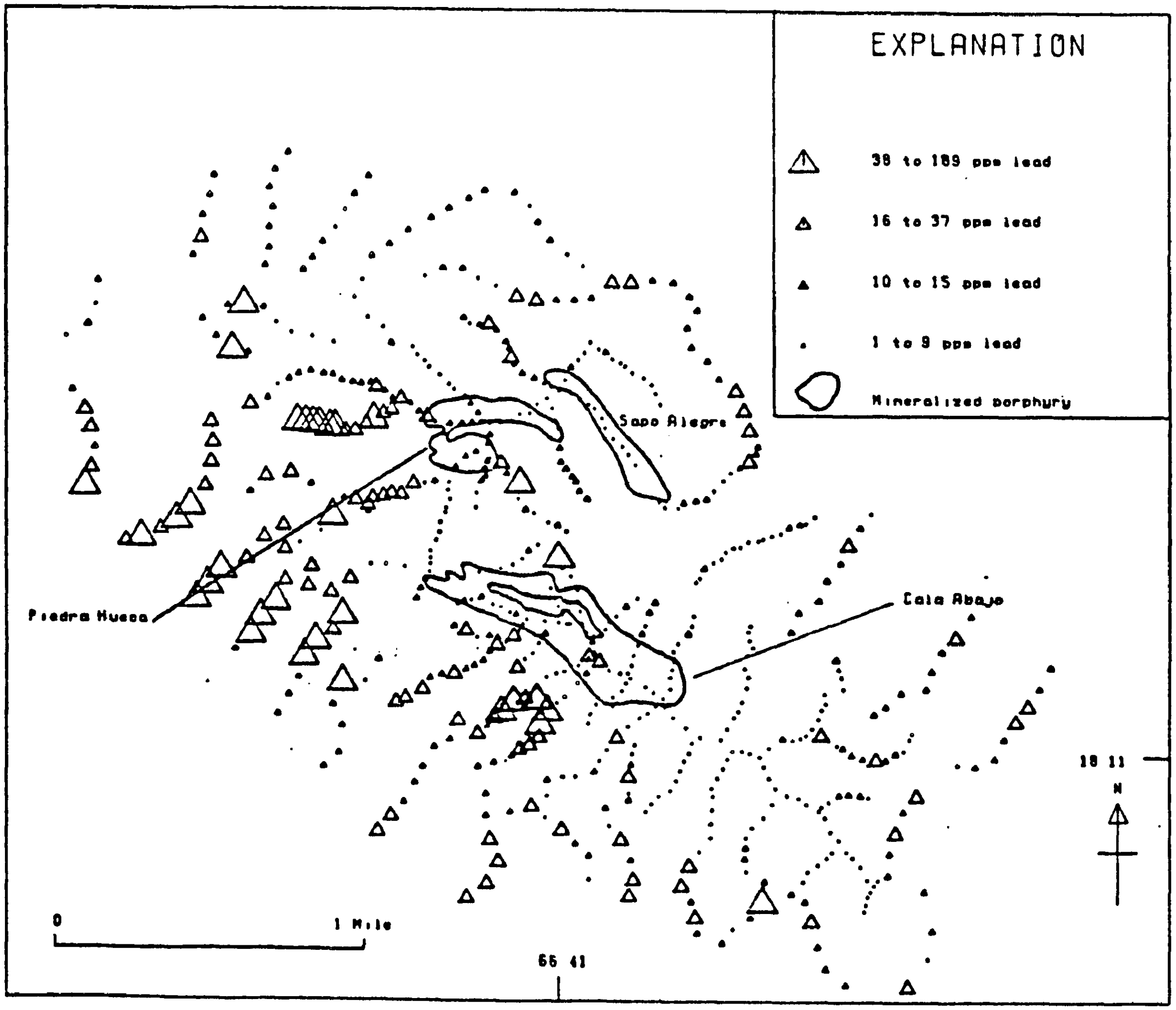

Figure 23. Distribution of lead in soil - Rio Vivi

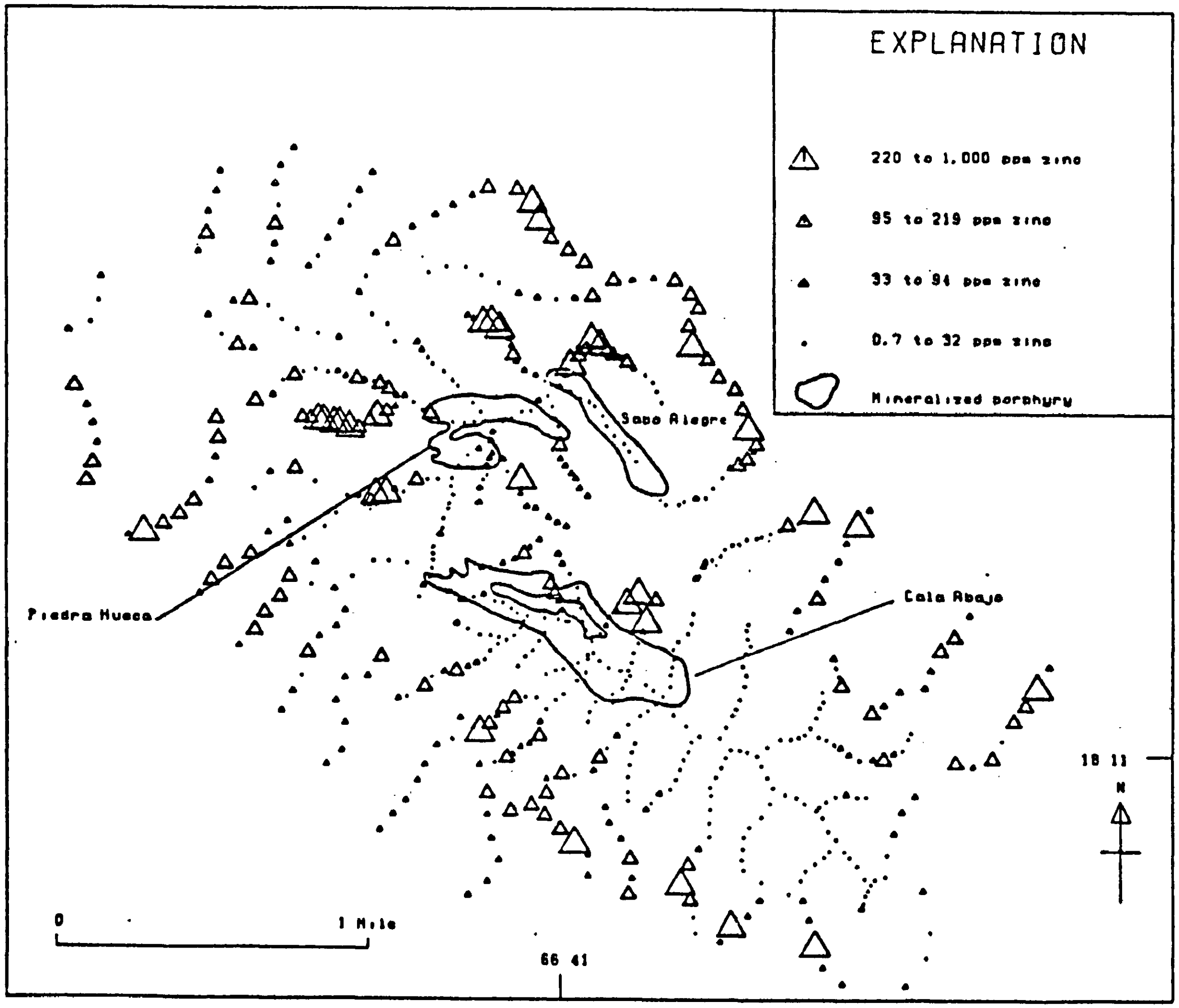

Figure 24. Distribution of zinc in soil - Rio Vivi

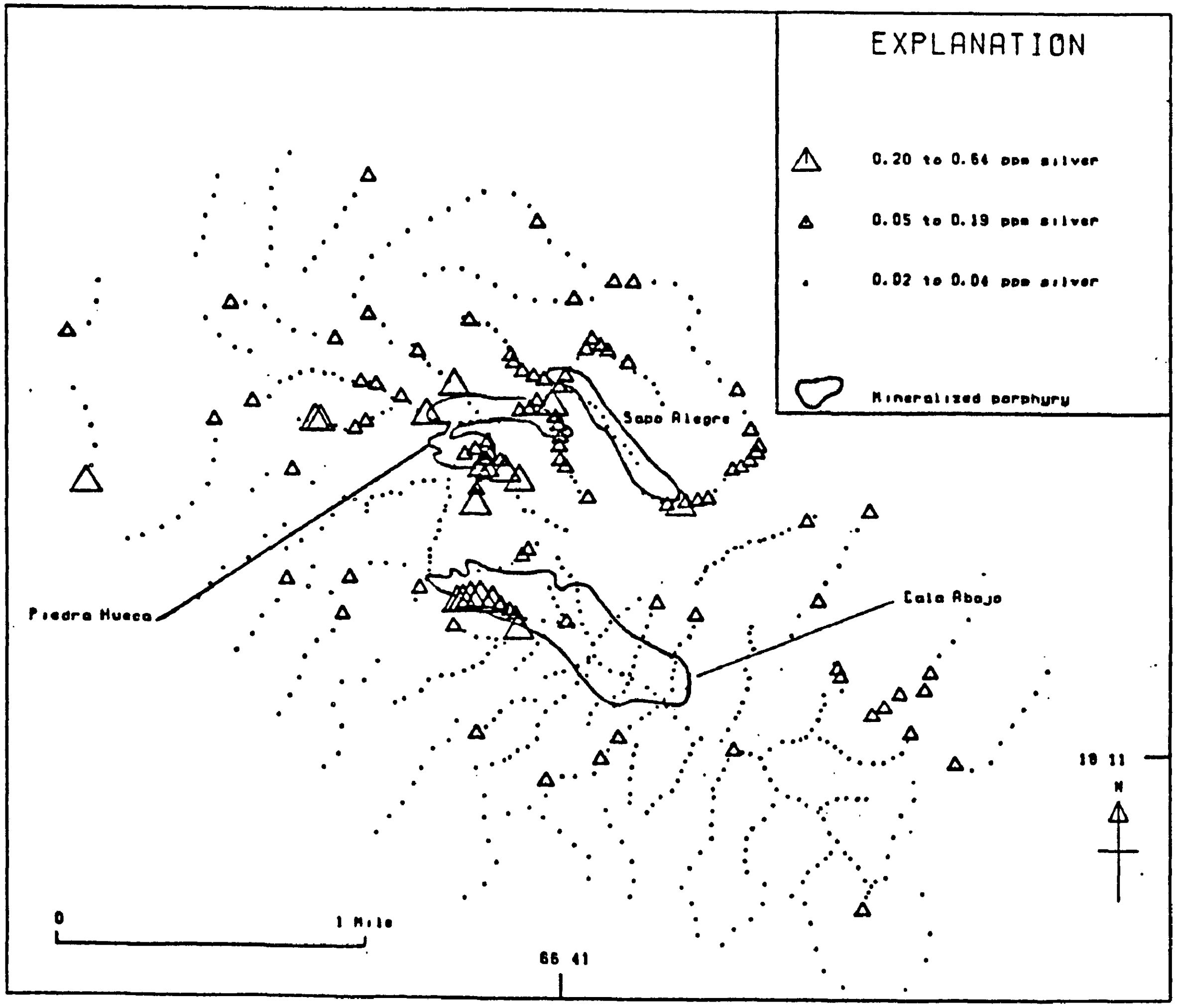

Figure 25. Distribution of silver in soil - Rio Vivi

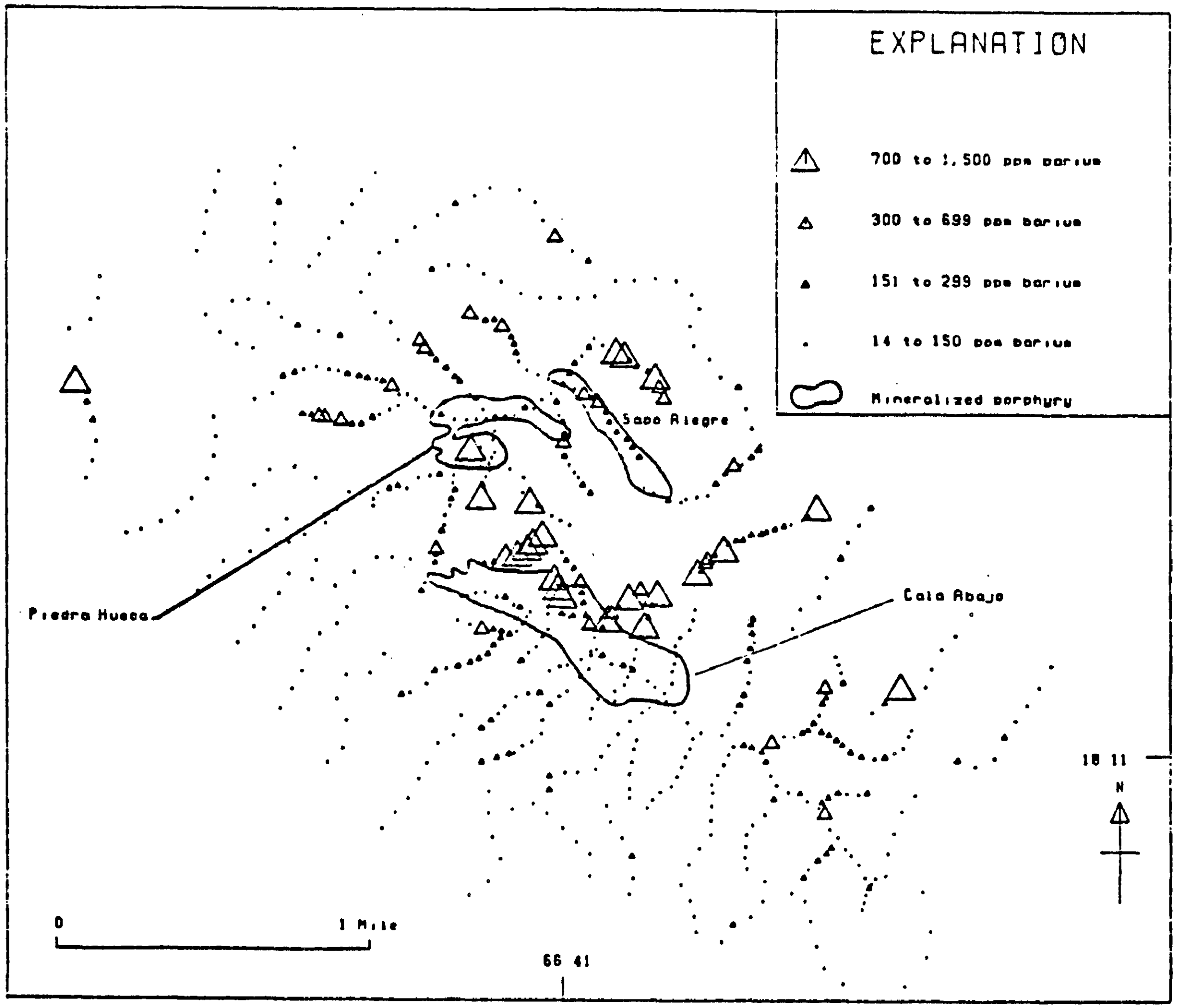

Figure 26. Distribution of barium in soil - Rio Vivi

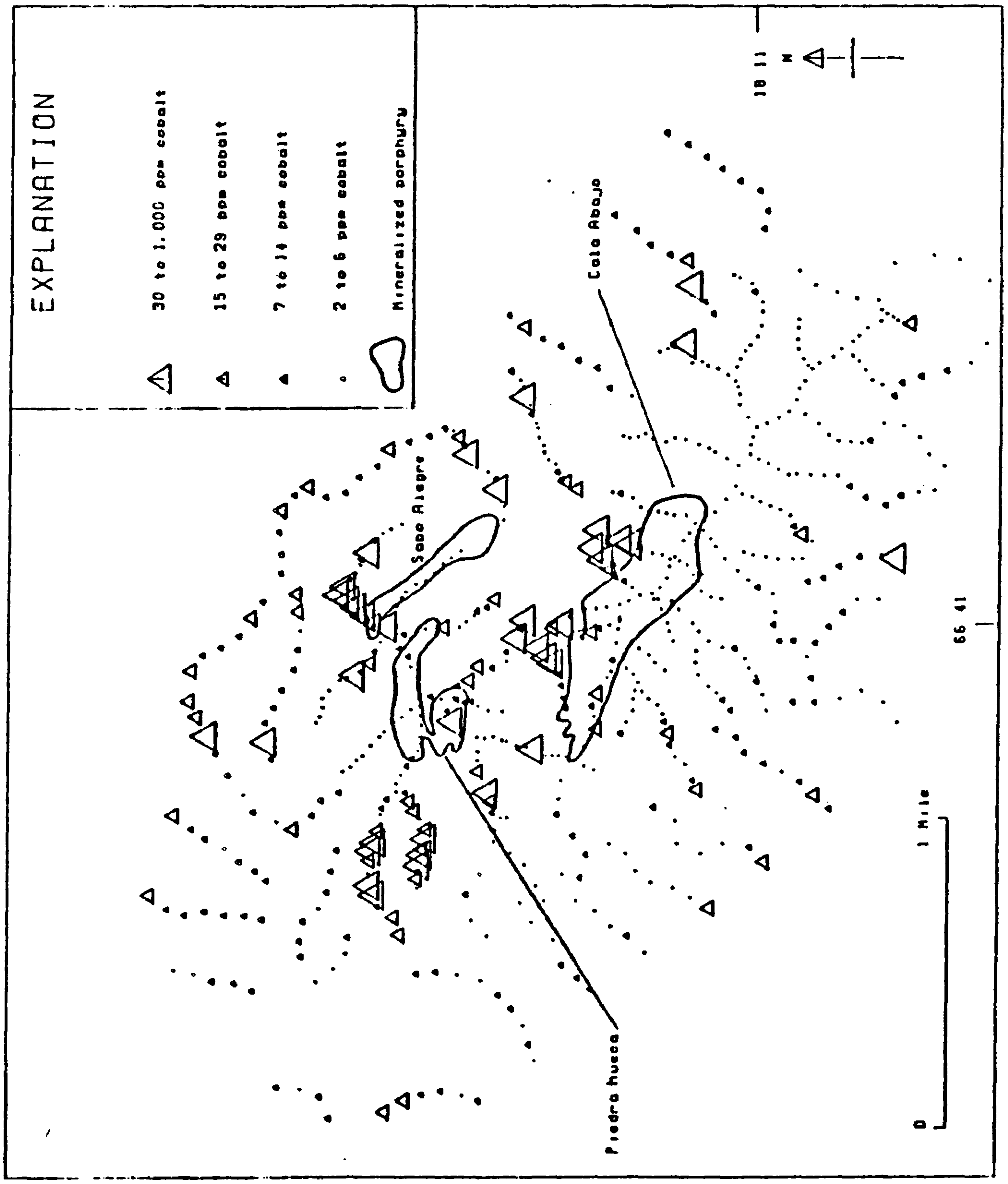

Figure 27. Distribution of cobalt in soil - Rio Vivi

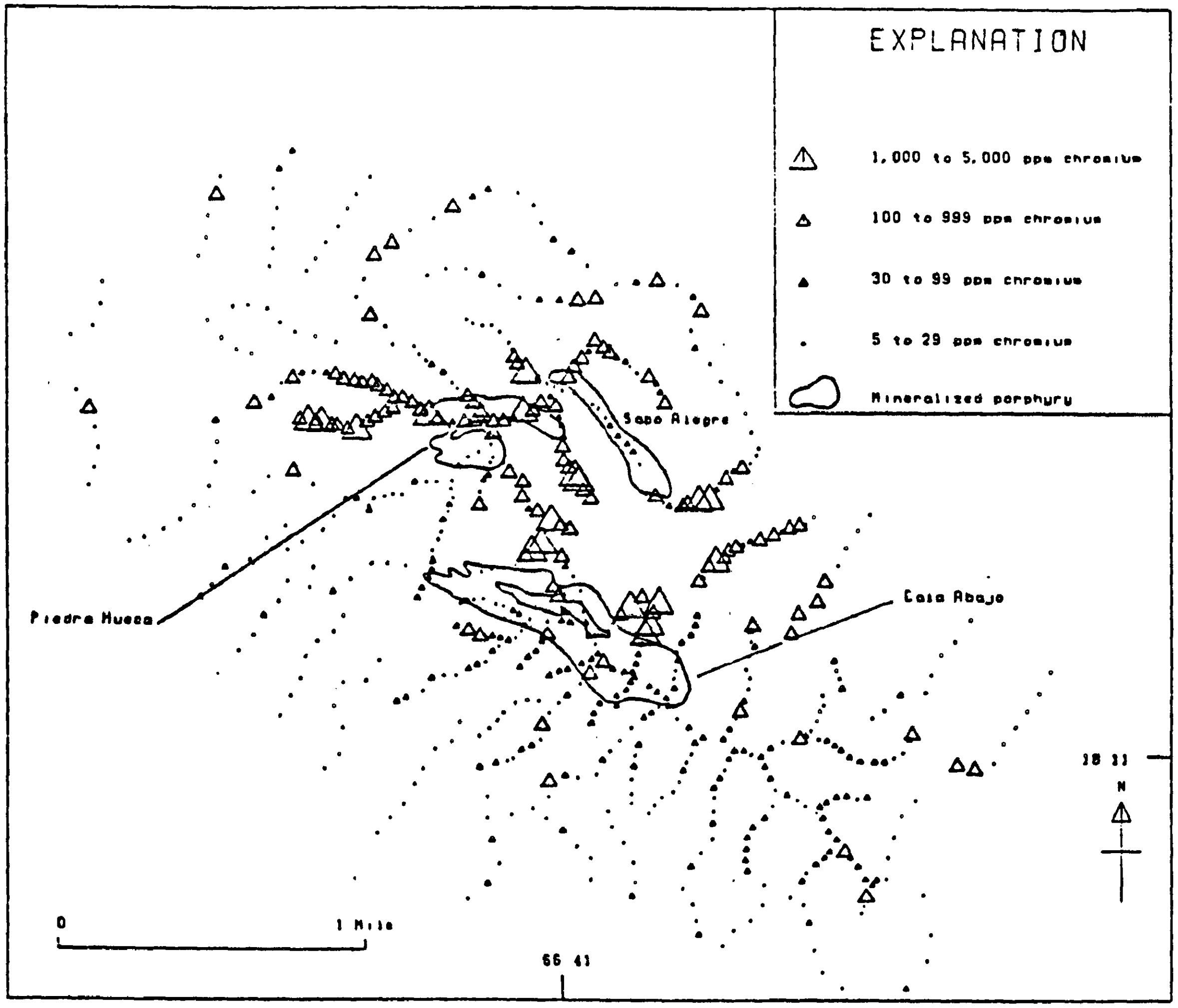

Figure 28. Distribution of chromium in soil - Rio Vivi

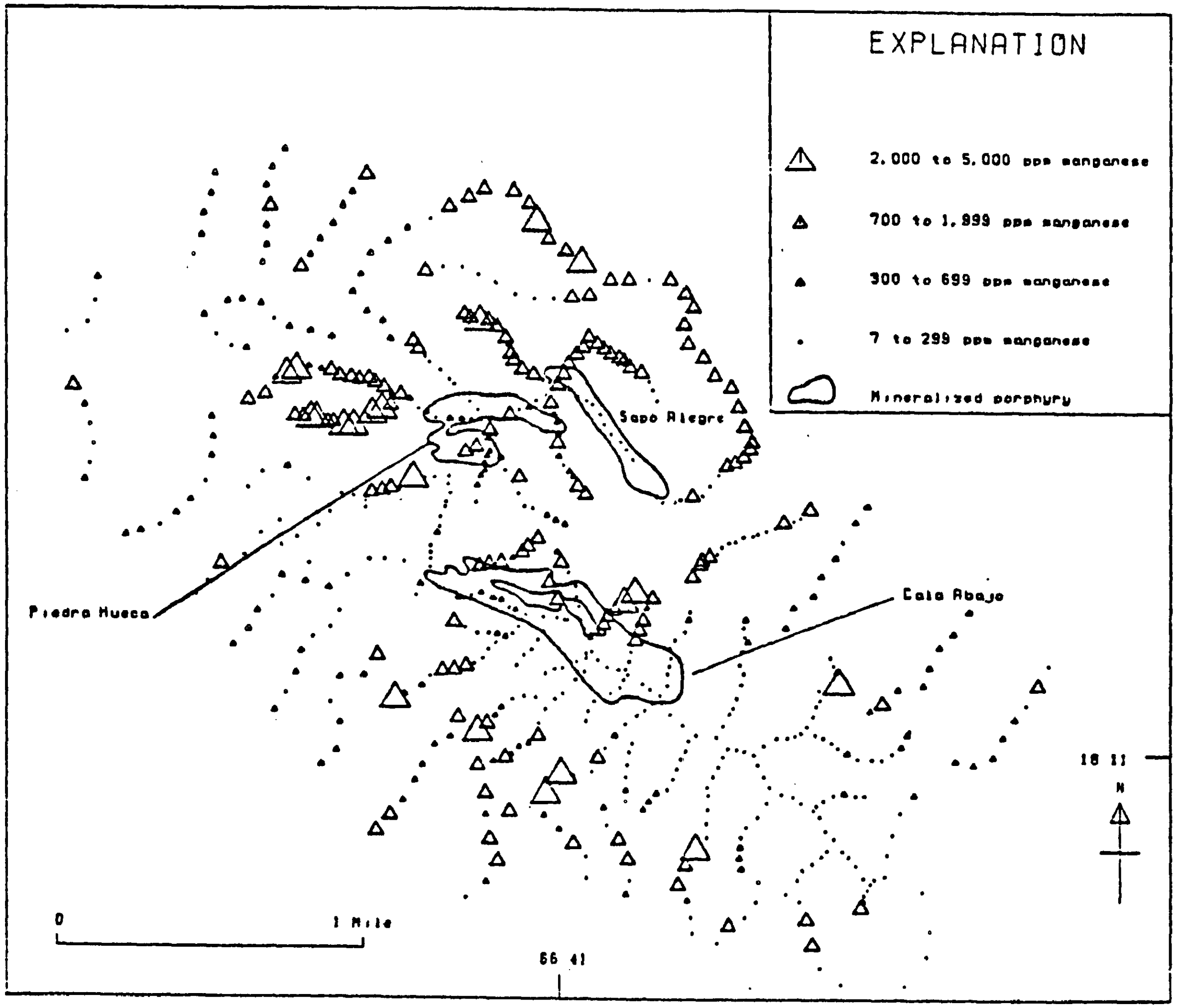

Figure 29. Distribution of manganese in soil - Rio Vivi

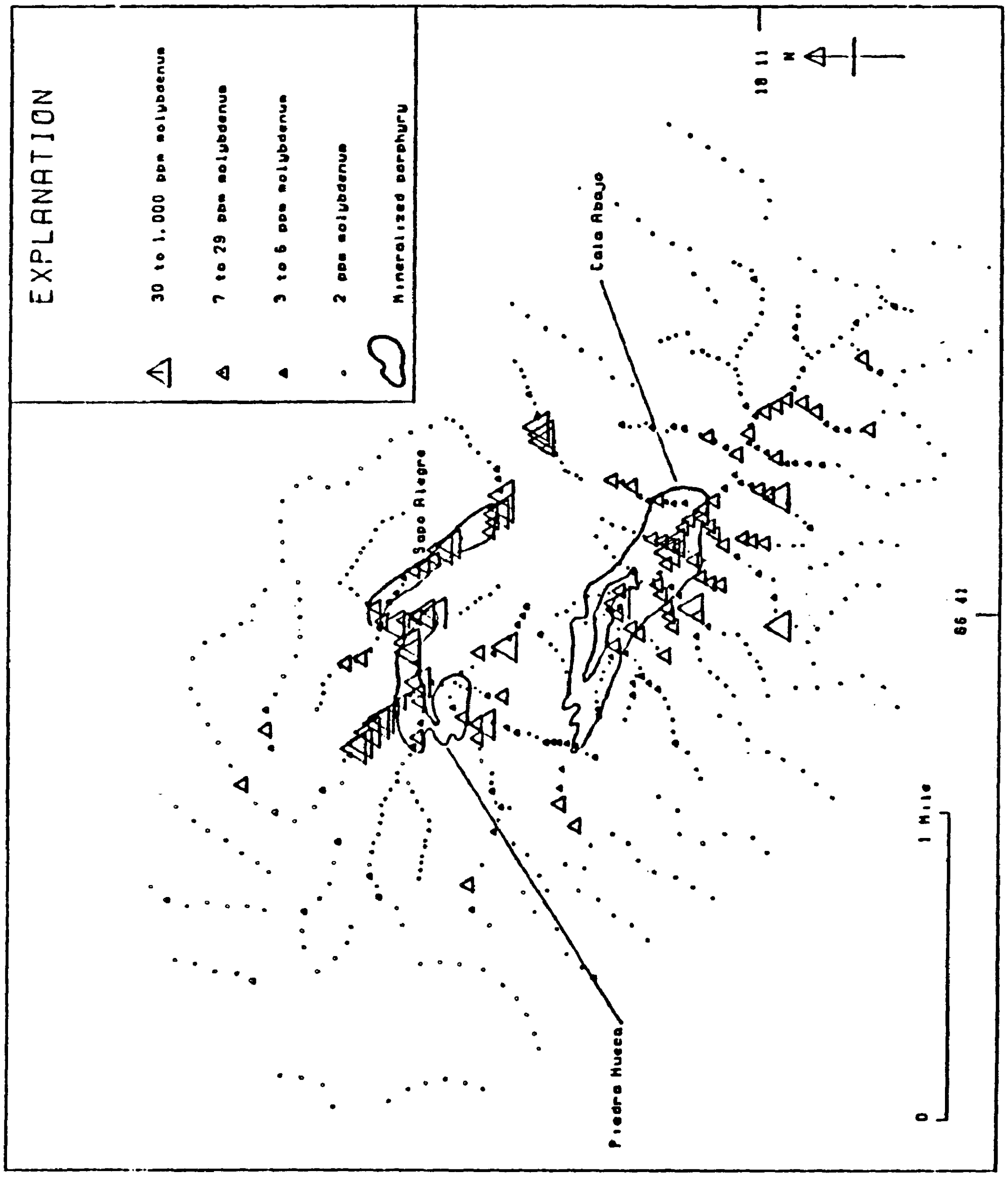

Figure 30. Distribution of molybdenum in soil - Rio Vivi

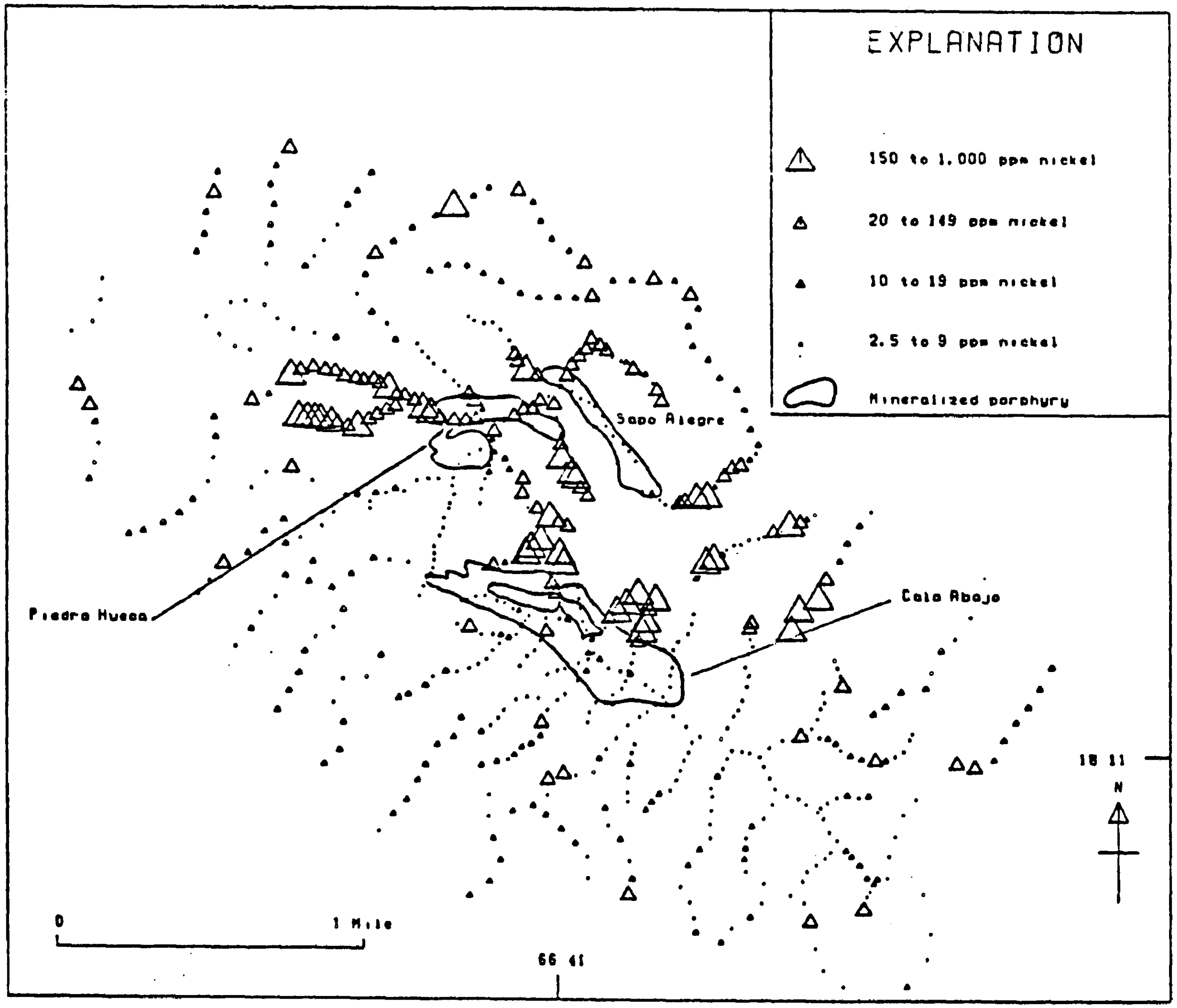

Figure 31. Distribution of nickel in soil - Rio Vivi

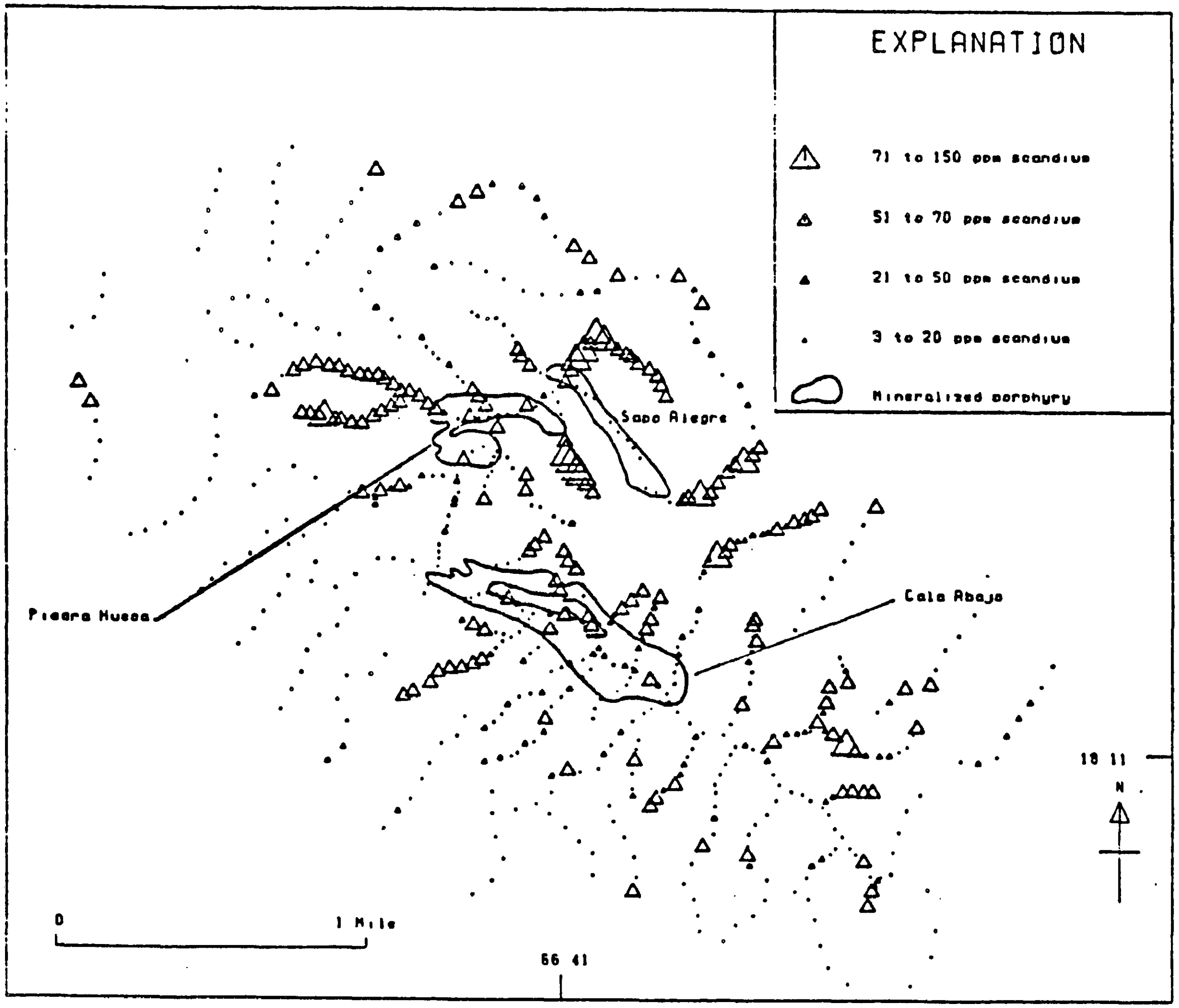

Figure 32. Distribution of scandium in soil - Rio Vivi

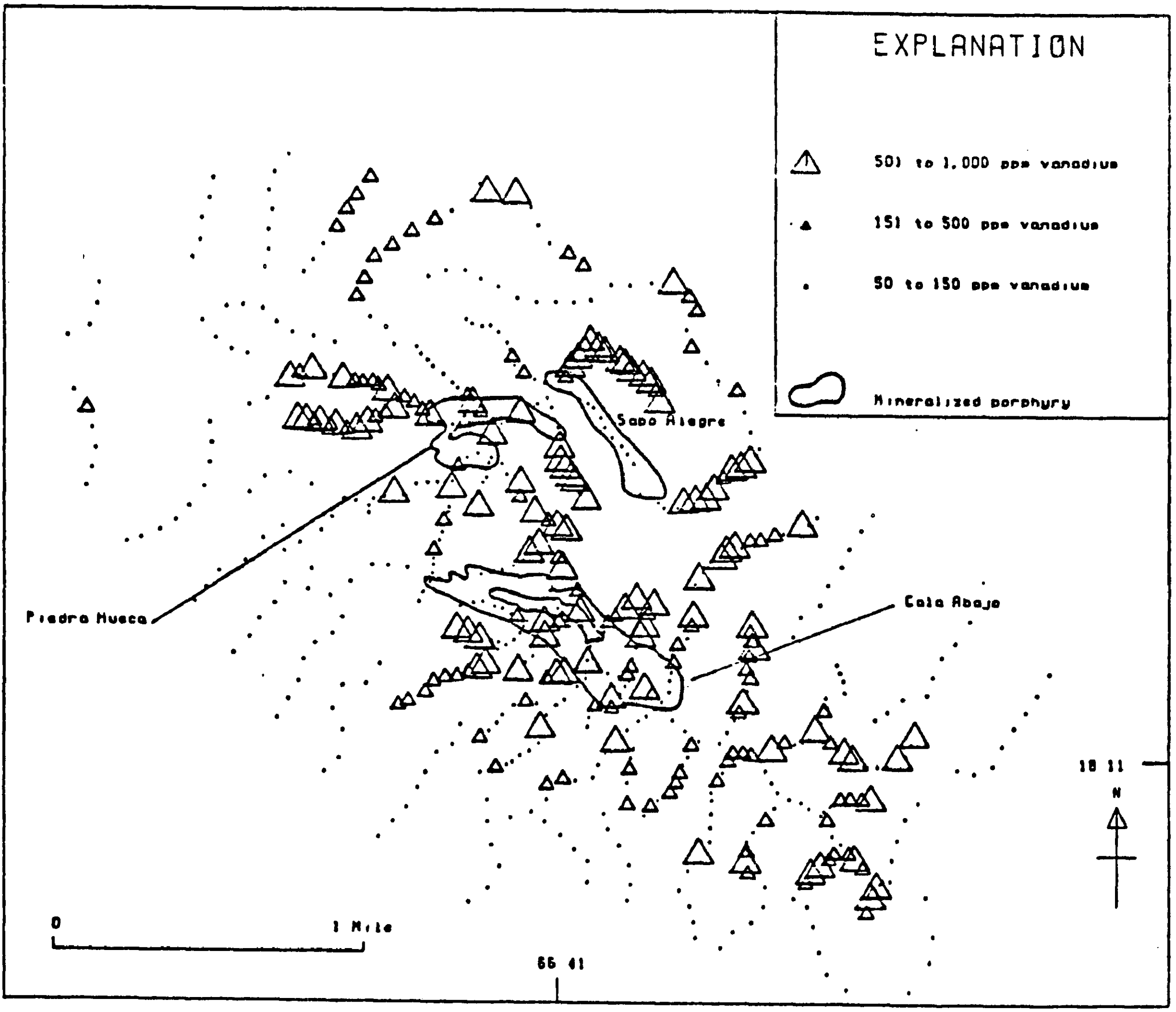

Figure 33. Distribution of vanadium in soil - Rio Vivi

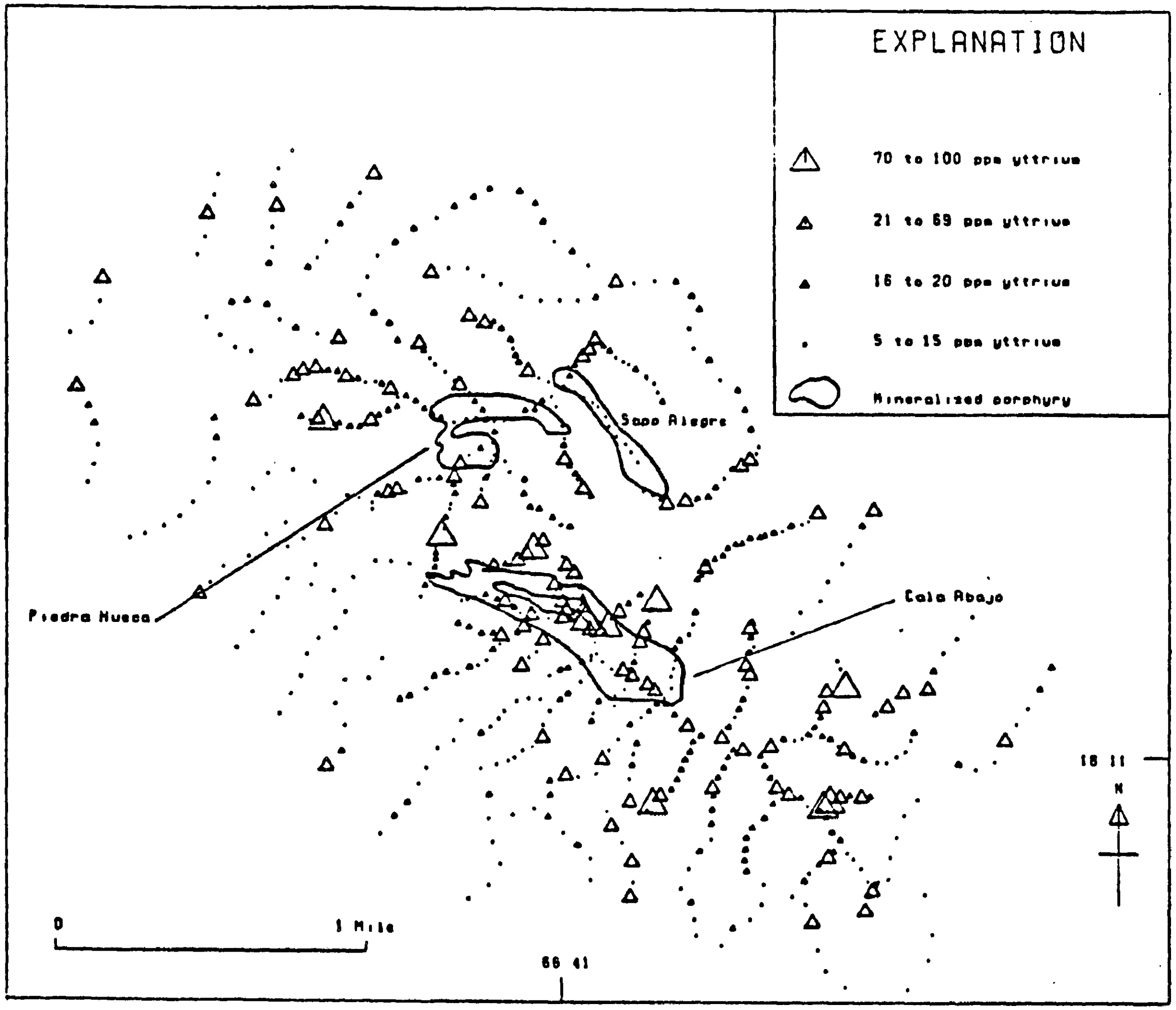

Figure 34. Distribution of yttrium in soil - Rio Vivi

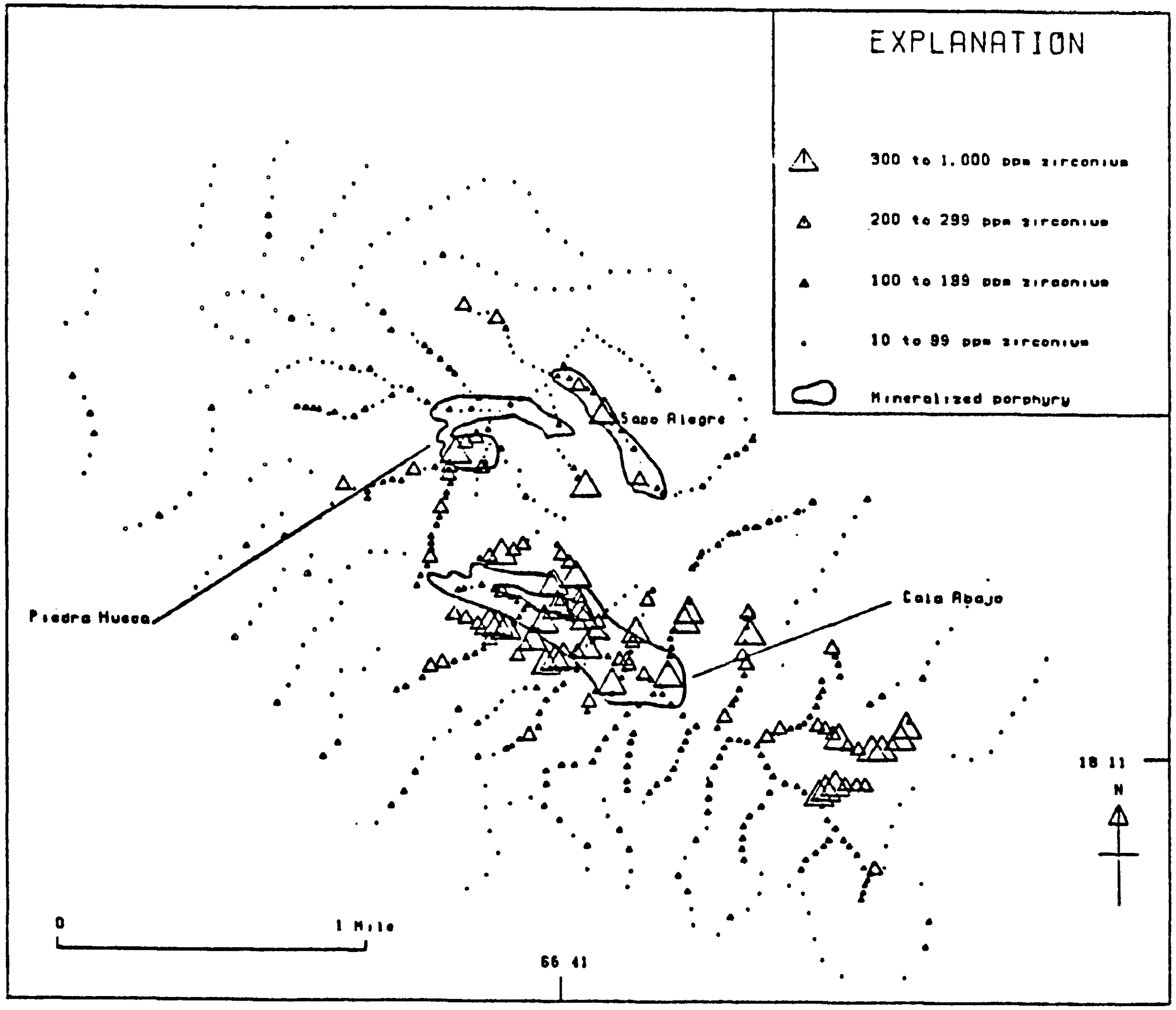

Figure 35. Distribution of zirconium in soil - Rio Vivi

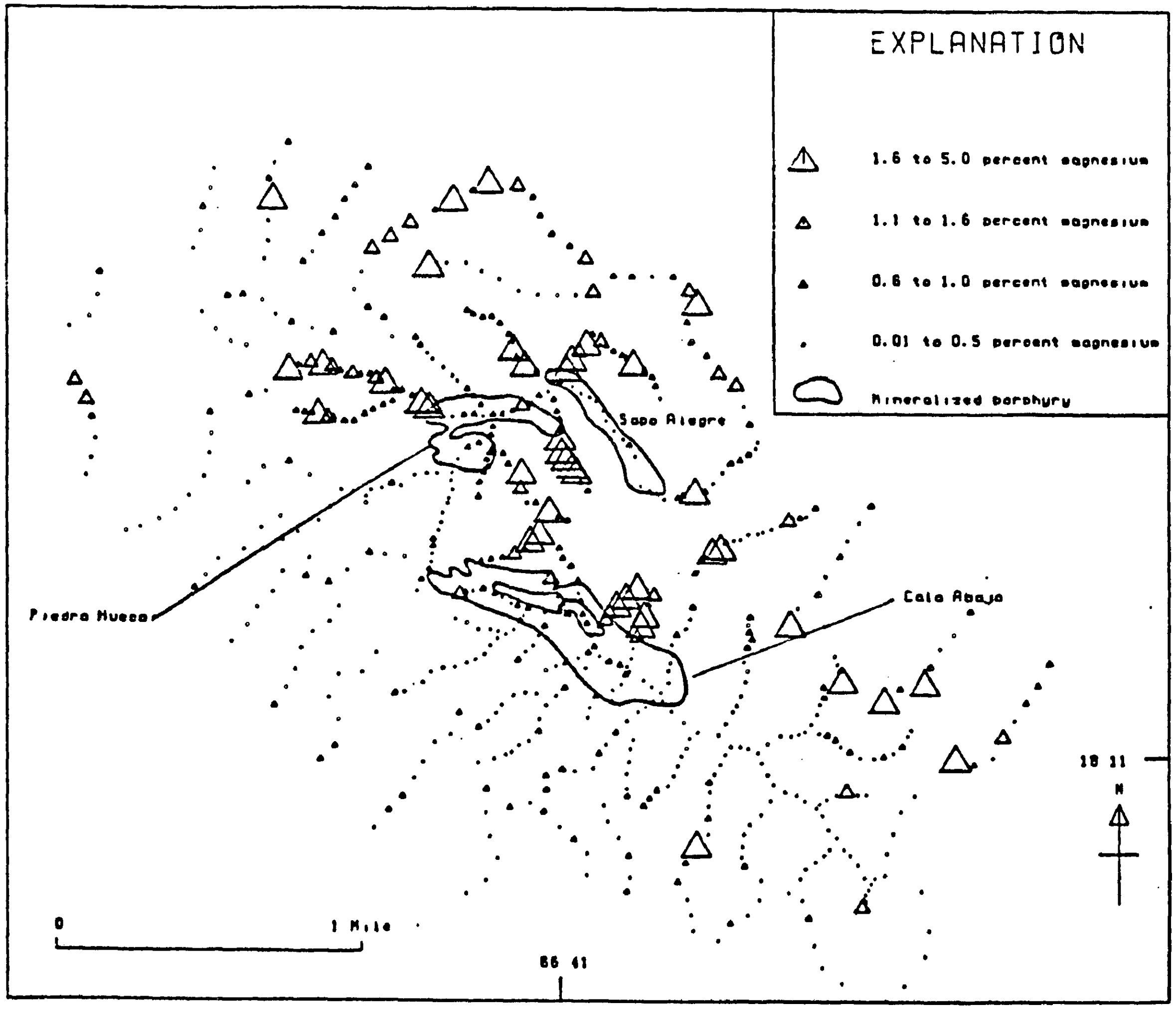

Figure 36. Distribution of magnesium in soil - Rio Vivi

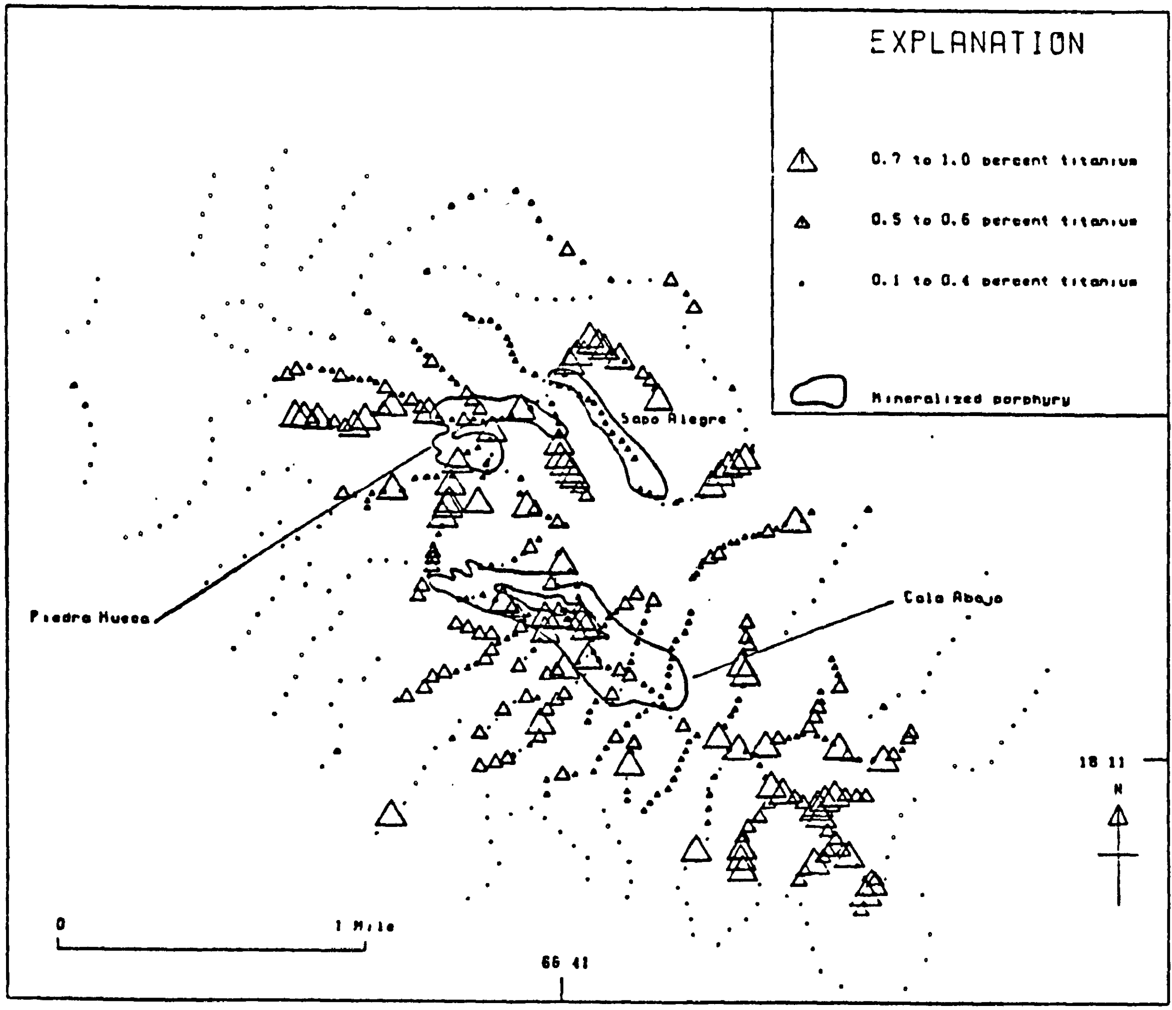

Figure 37. Distribution of titanium in soil - Rio Vivi

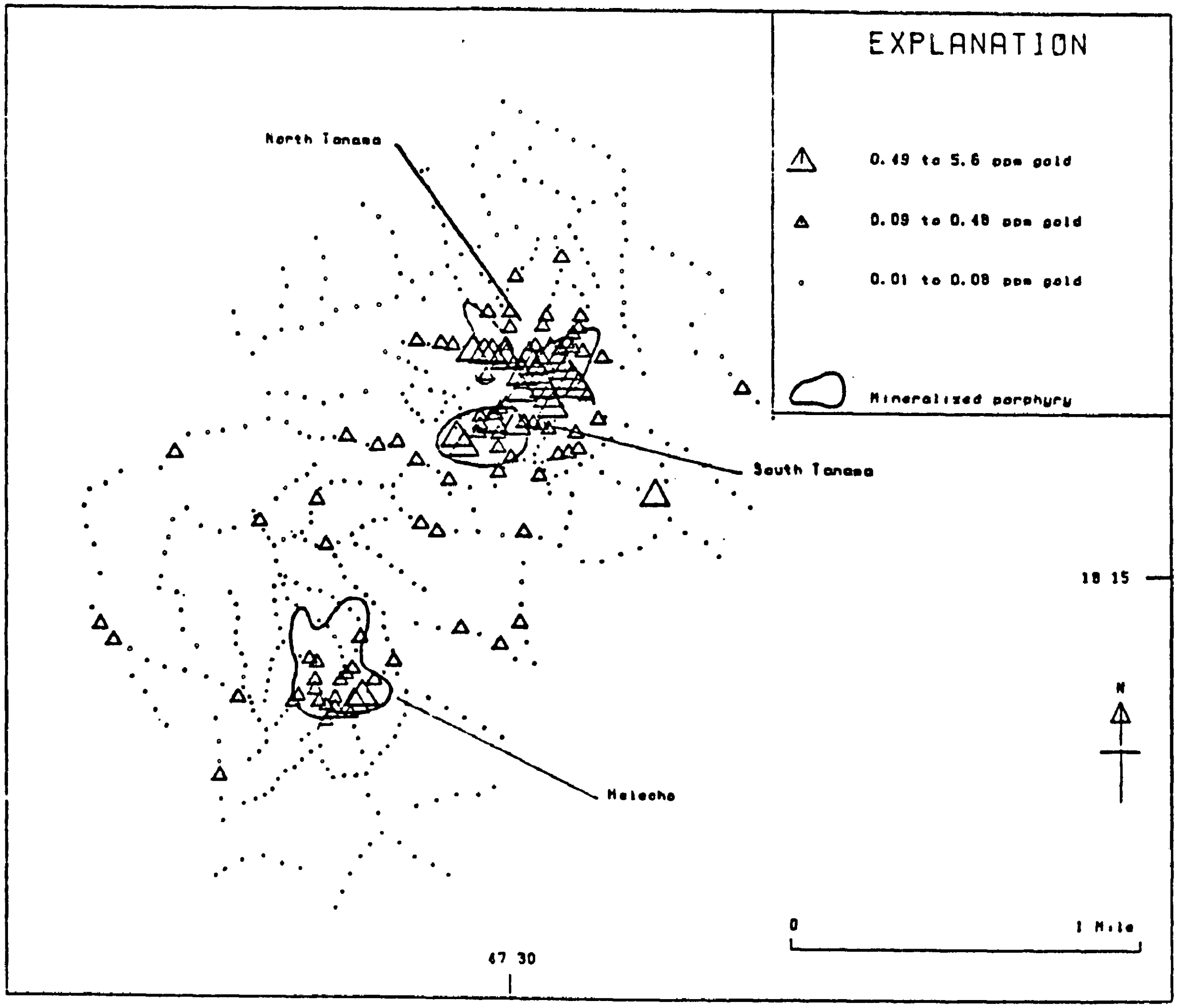

Figure 38. Distribution of gold in soil - Rio Tanama

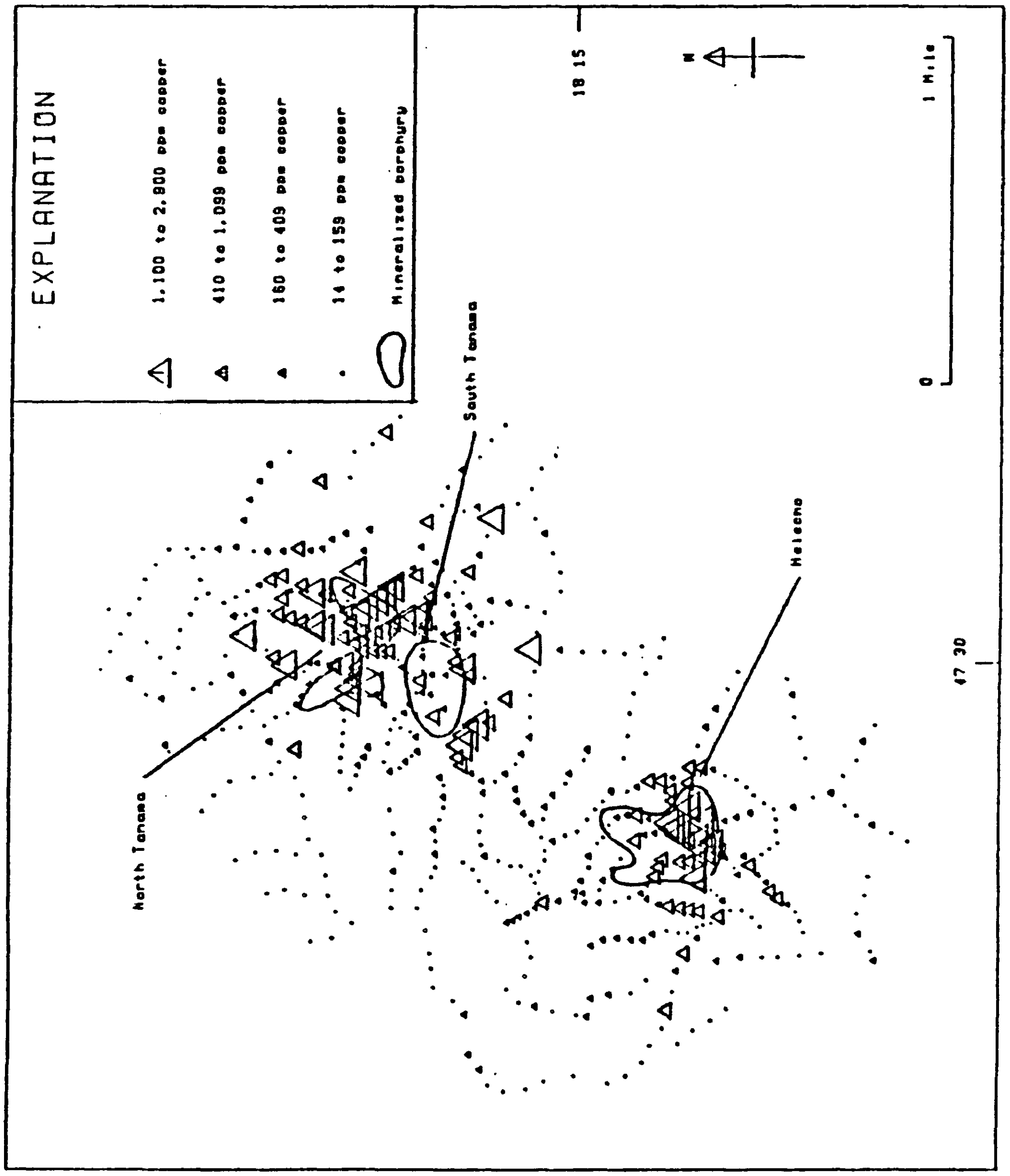

Figure 39. Distribution of copper in soil - Rio Tanama

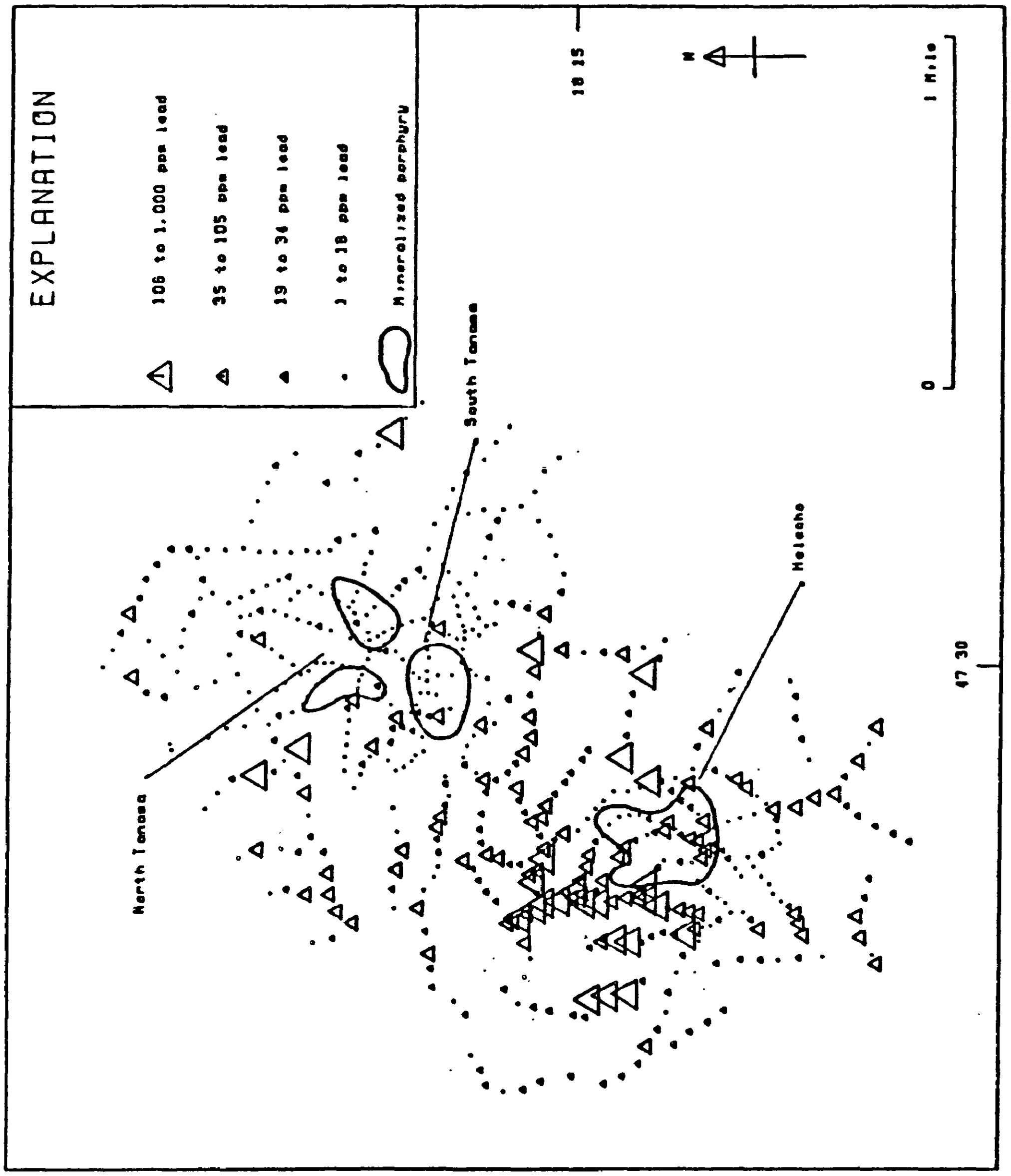

Figure 40. Distribution of lead in soil - Rio Tanama

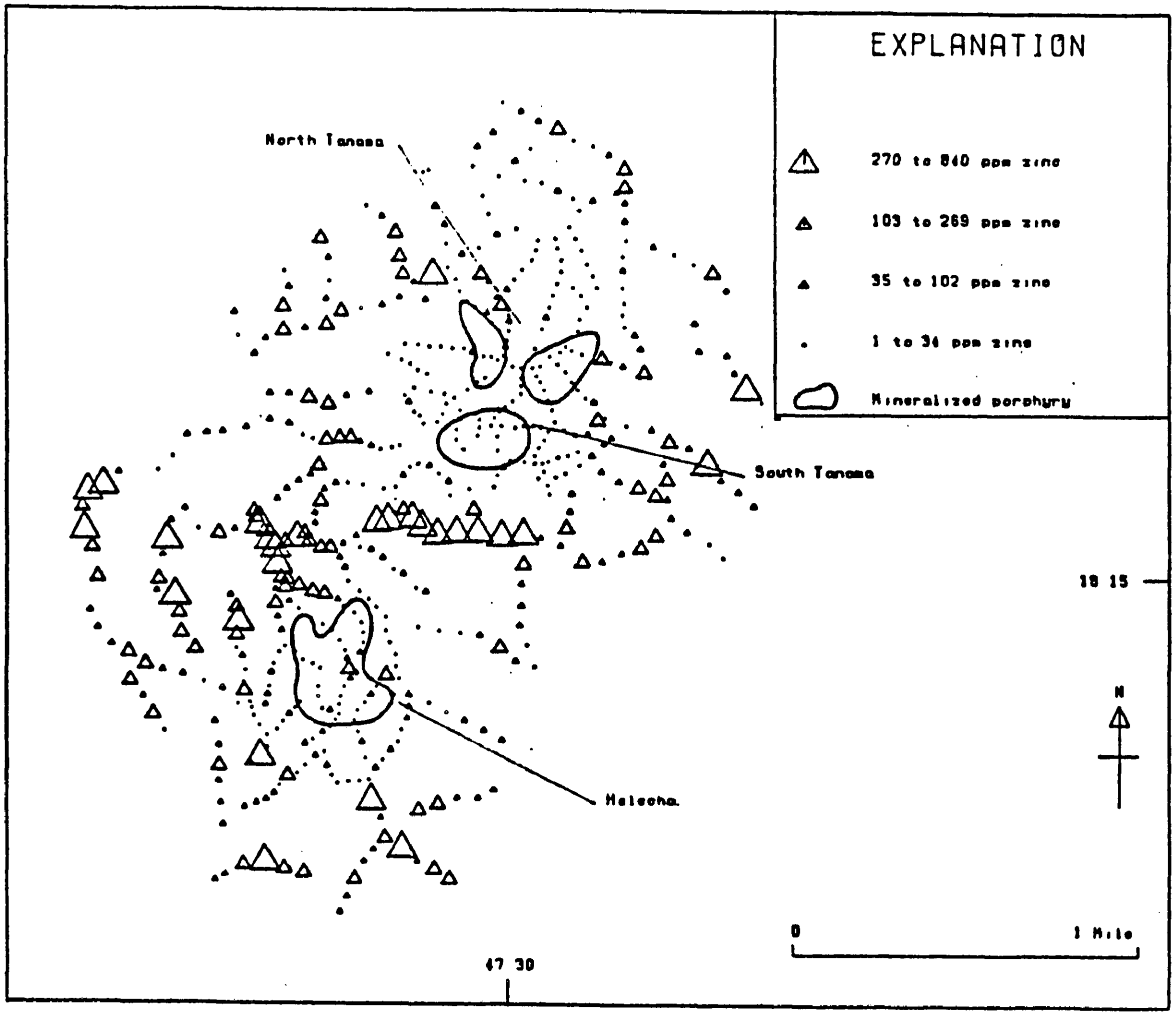

Figure 41. Distribution of zinc in soil - Rio Tanama

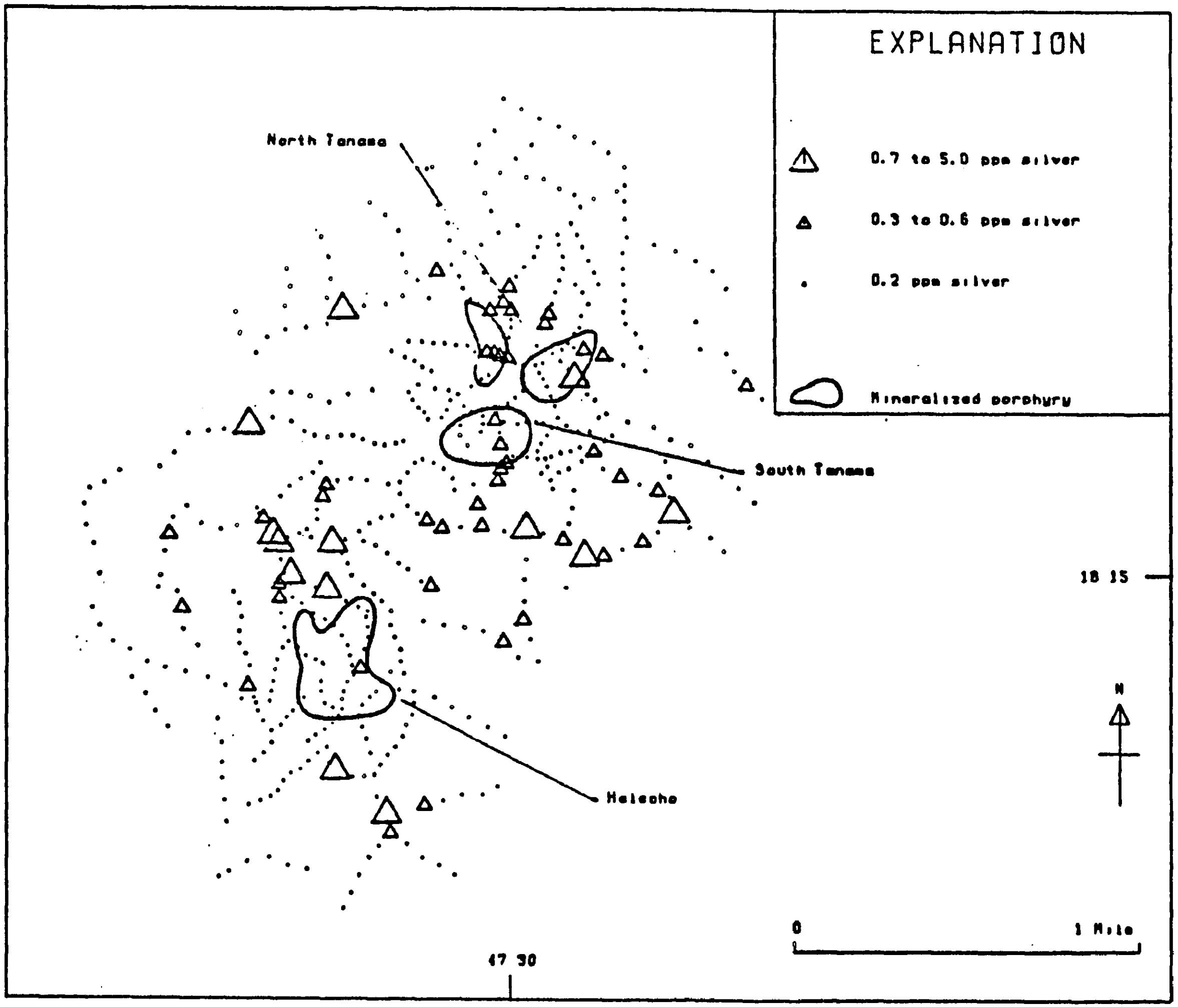

Figure 42. Distribution of silver in soil - Rio Tanama

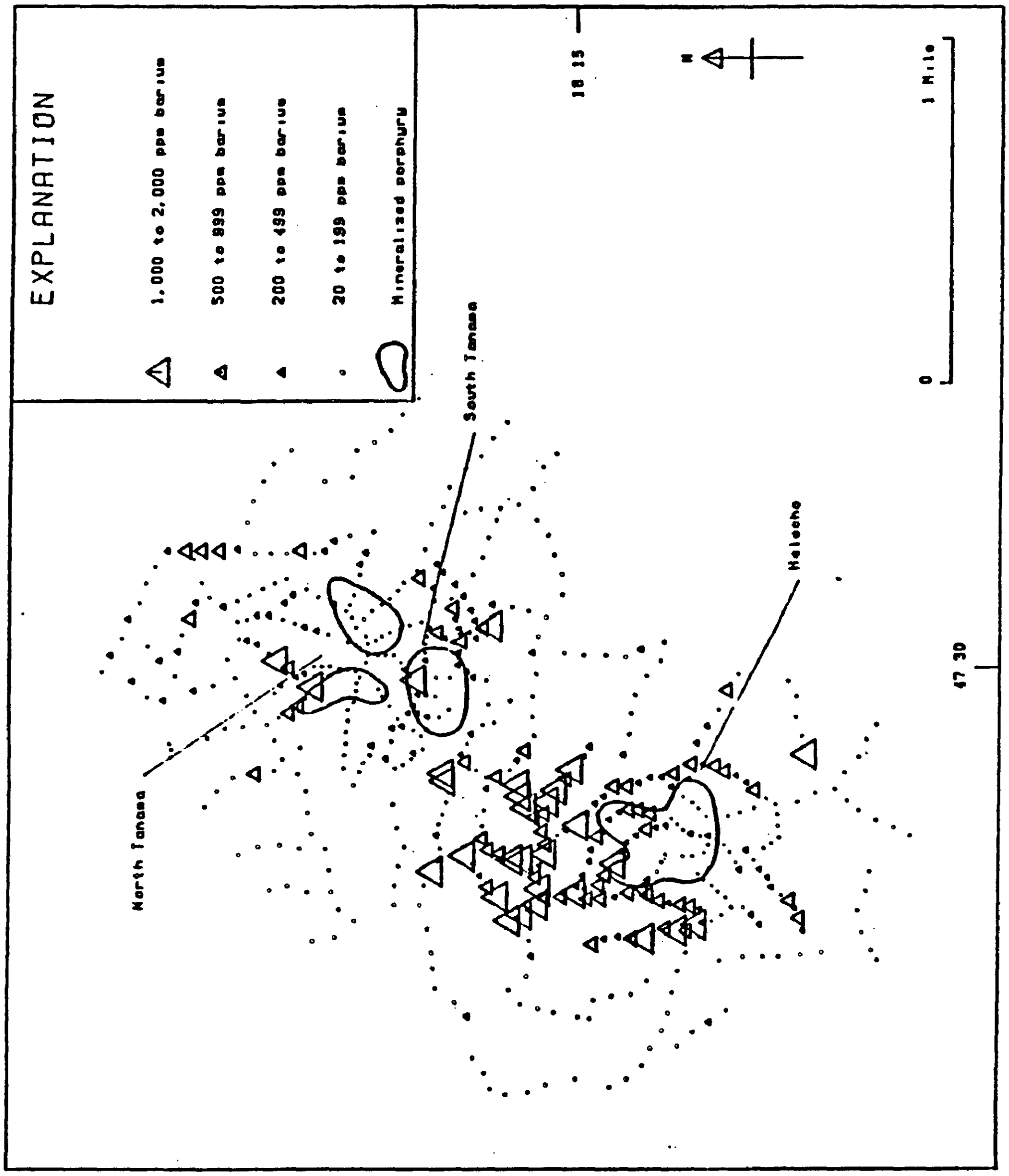

Figure 43. Distribution of barium in soil - Rio Tanama

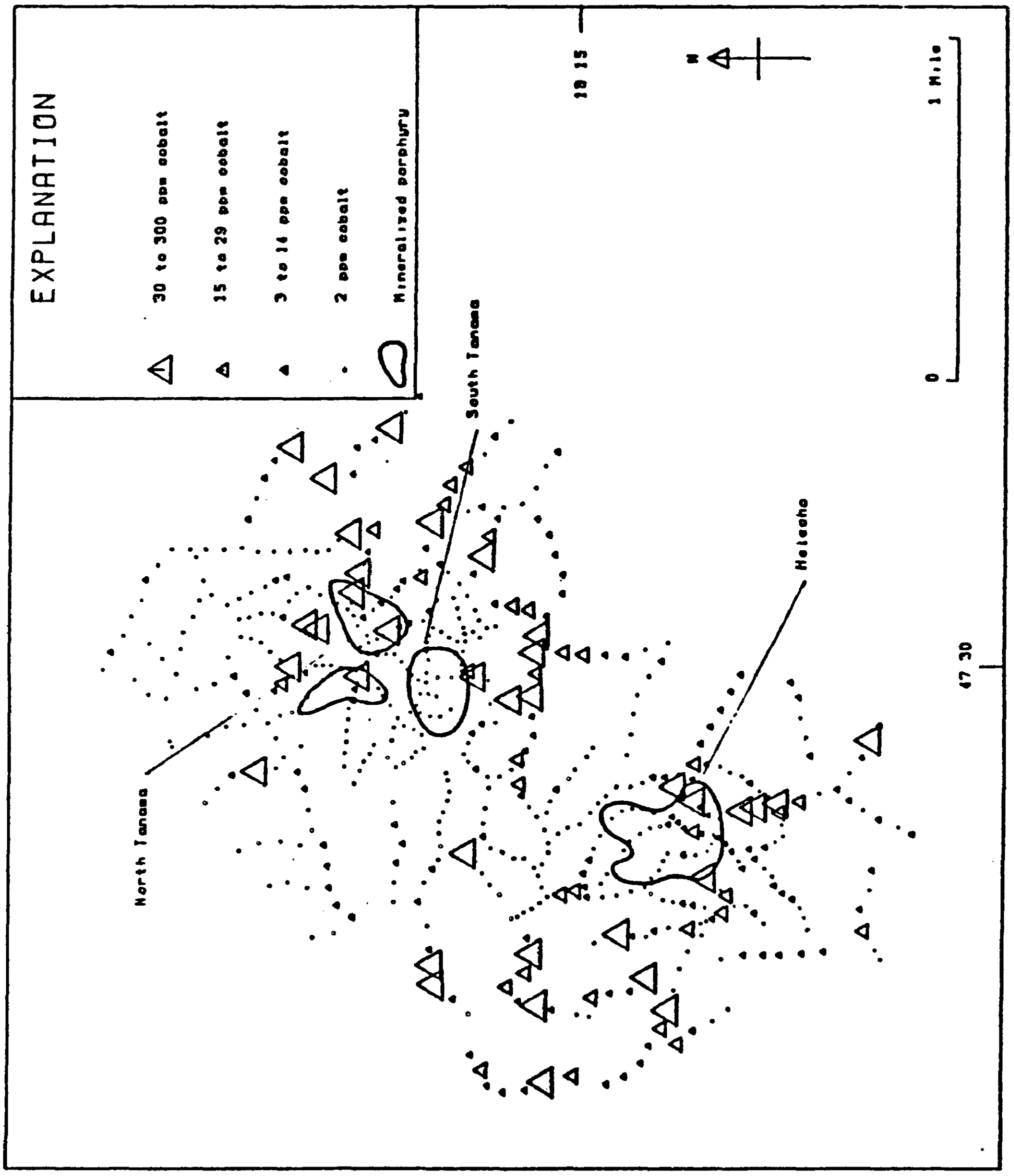

Figure 44. Distribution of cobalt in soil - Rio Tanama

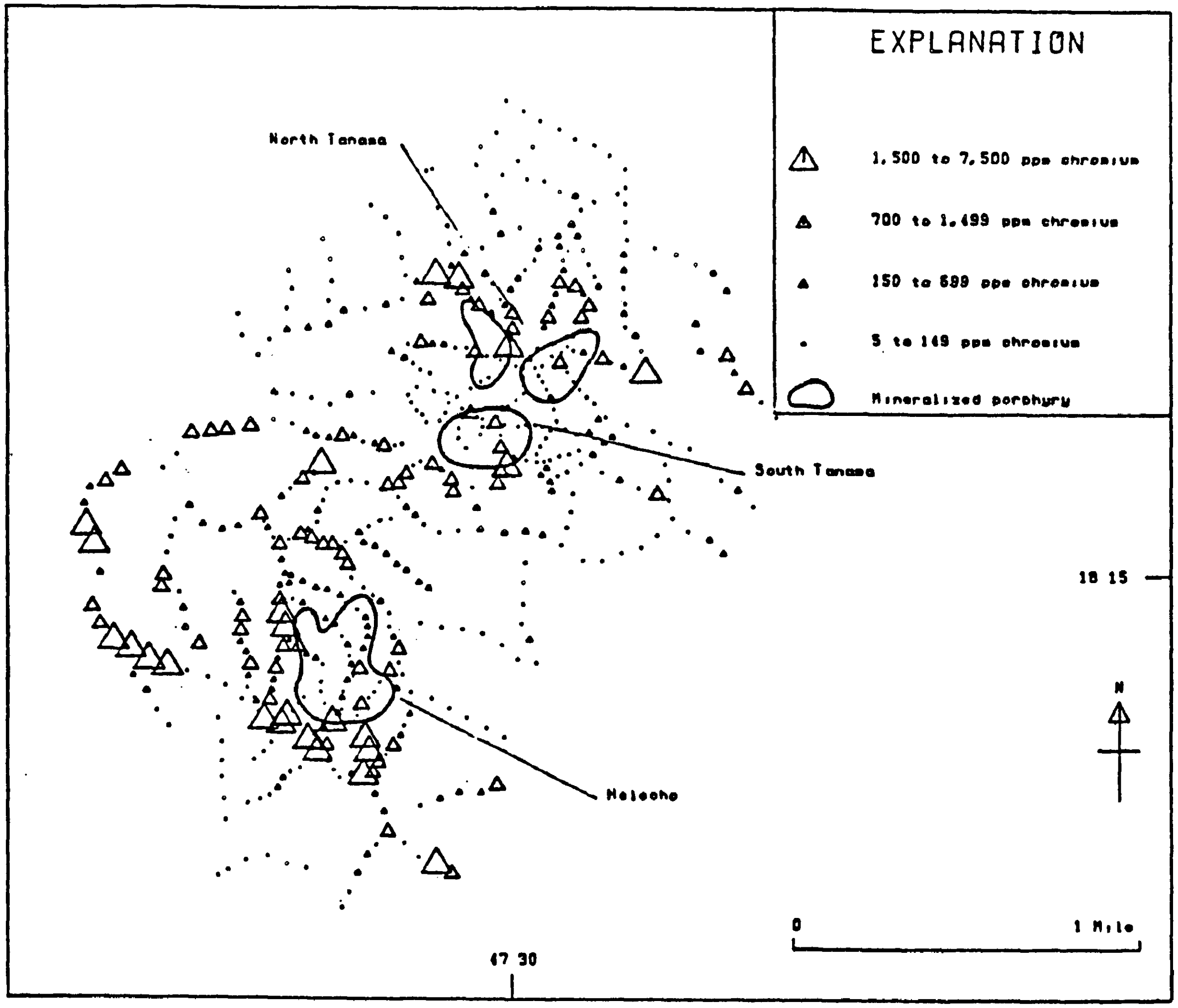

Figure 45. Distribution of chromium in soil - Rio Tanama

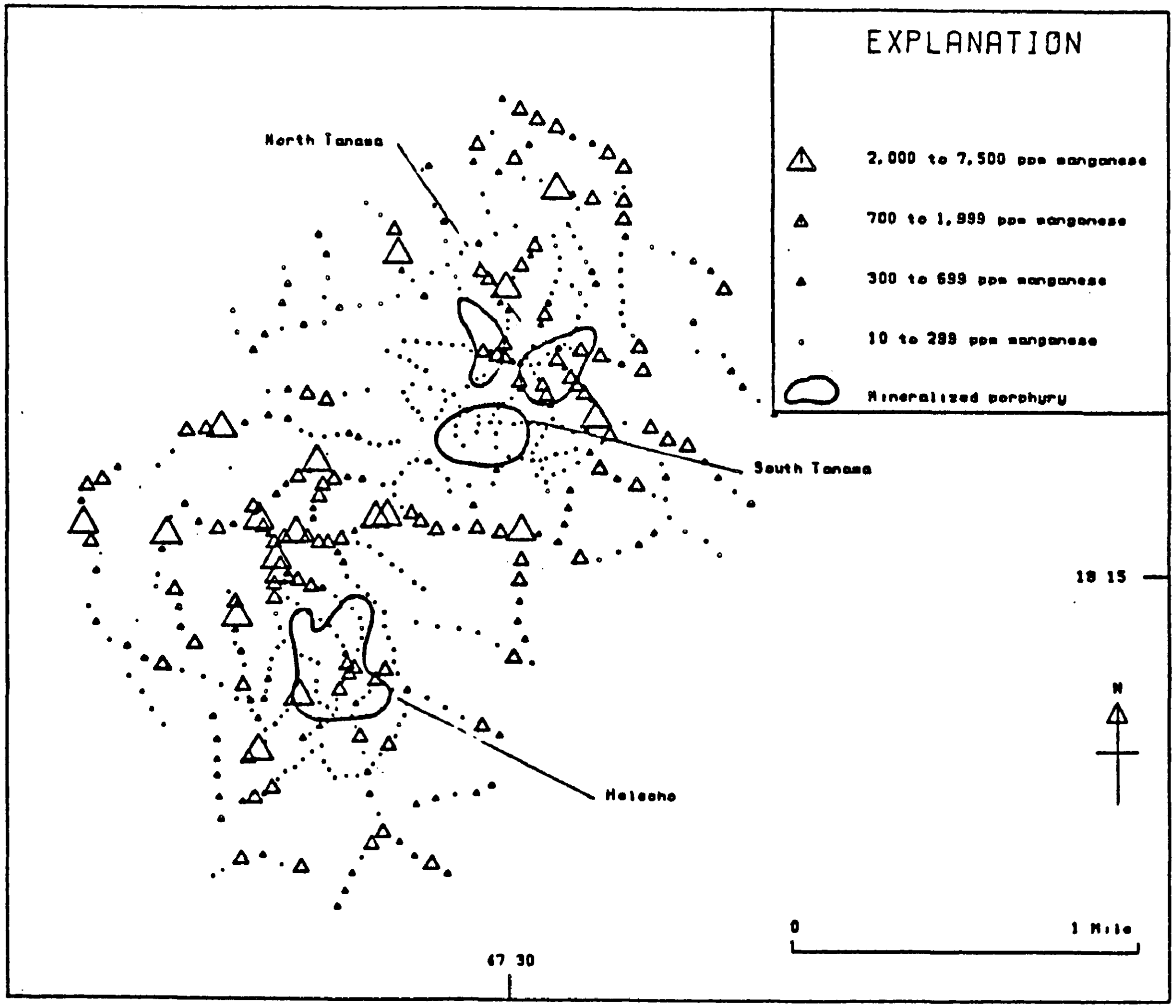

Figure 46. Distribution of manganese in soil - Rio Tanama

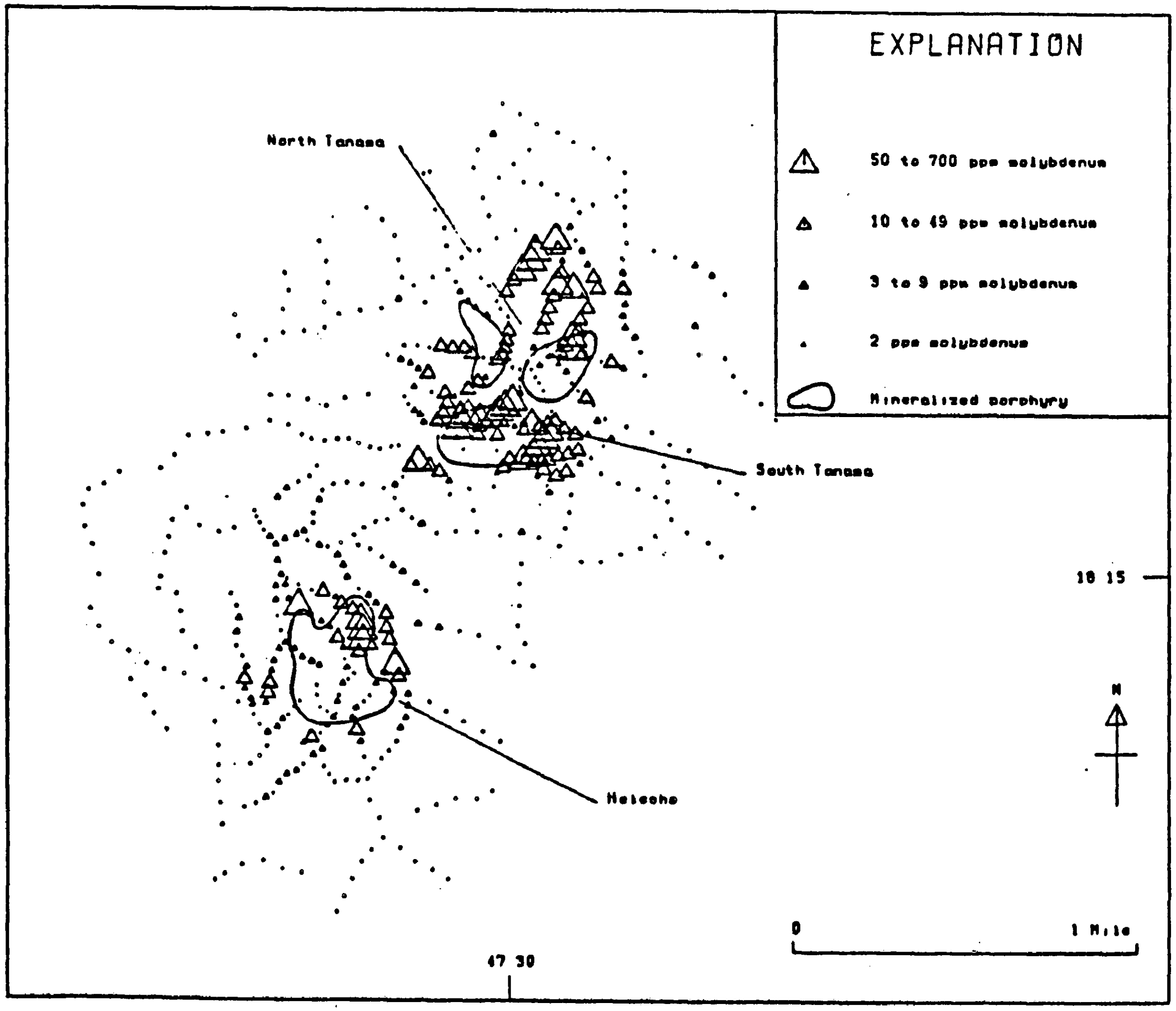

Figure 47. Distribution of molybdenum in soil - Rio Tanama

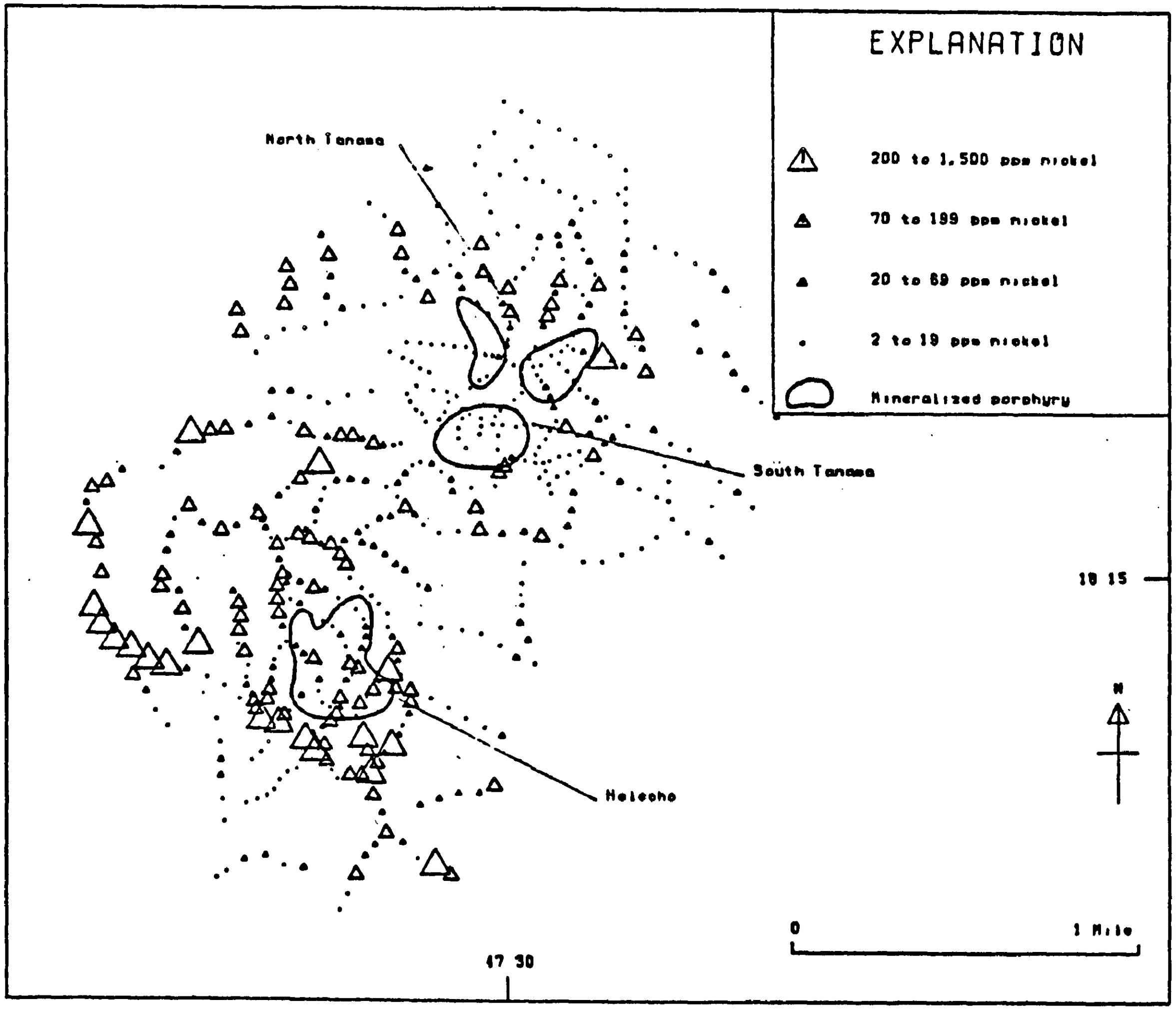

Figure 48. Distribution of nickel in soil - Rio Tanama

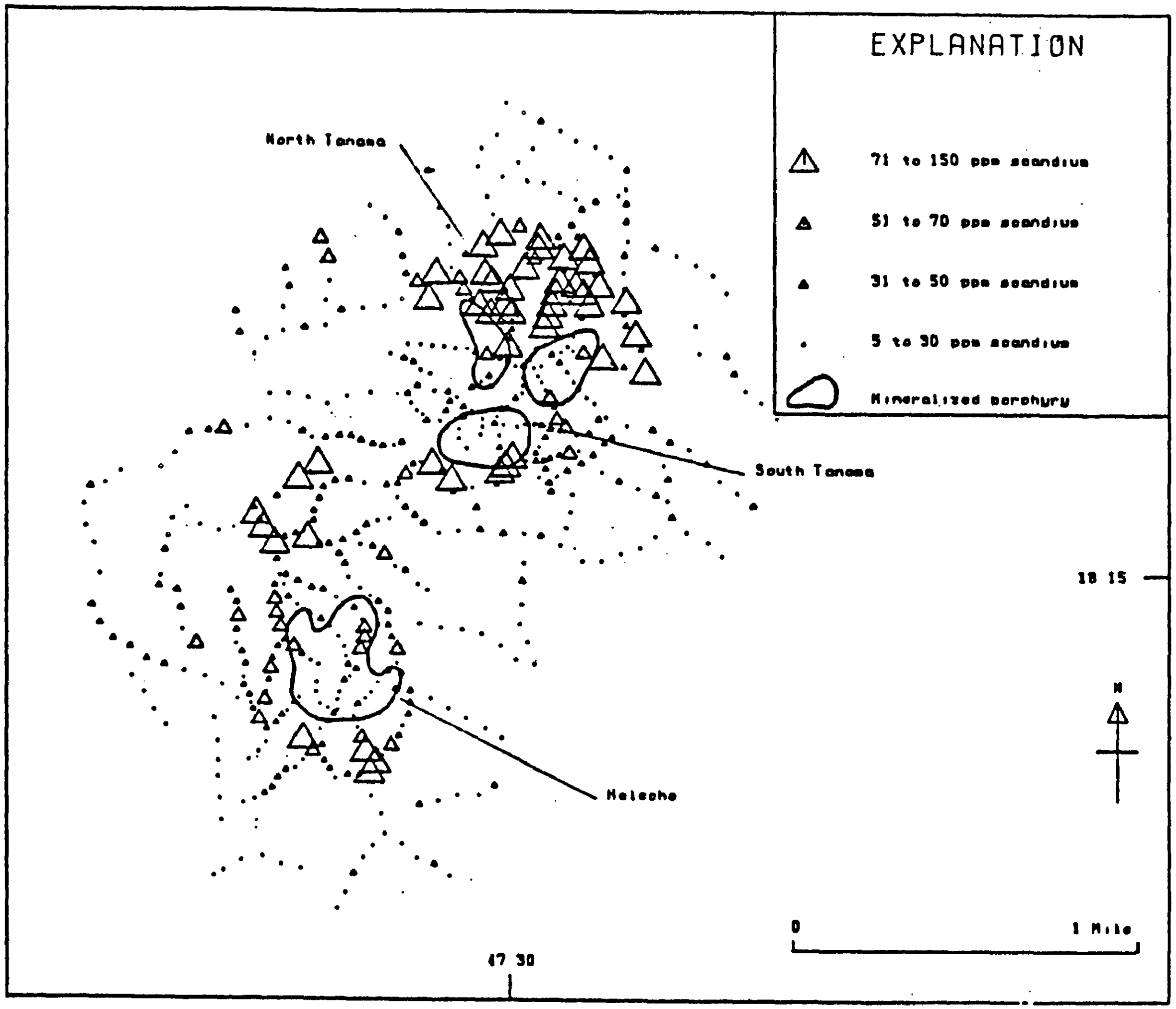

Figure 49. Distribution of scandium in soil - Rio Tanama

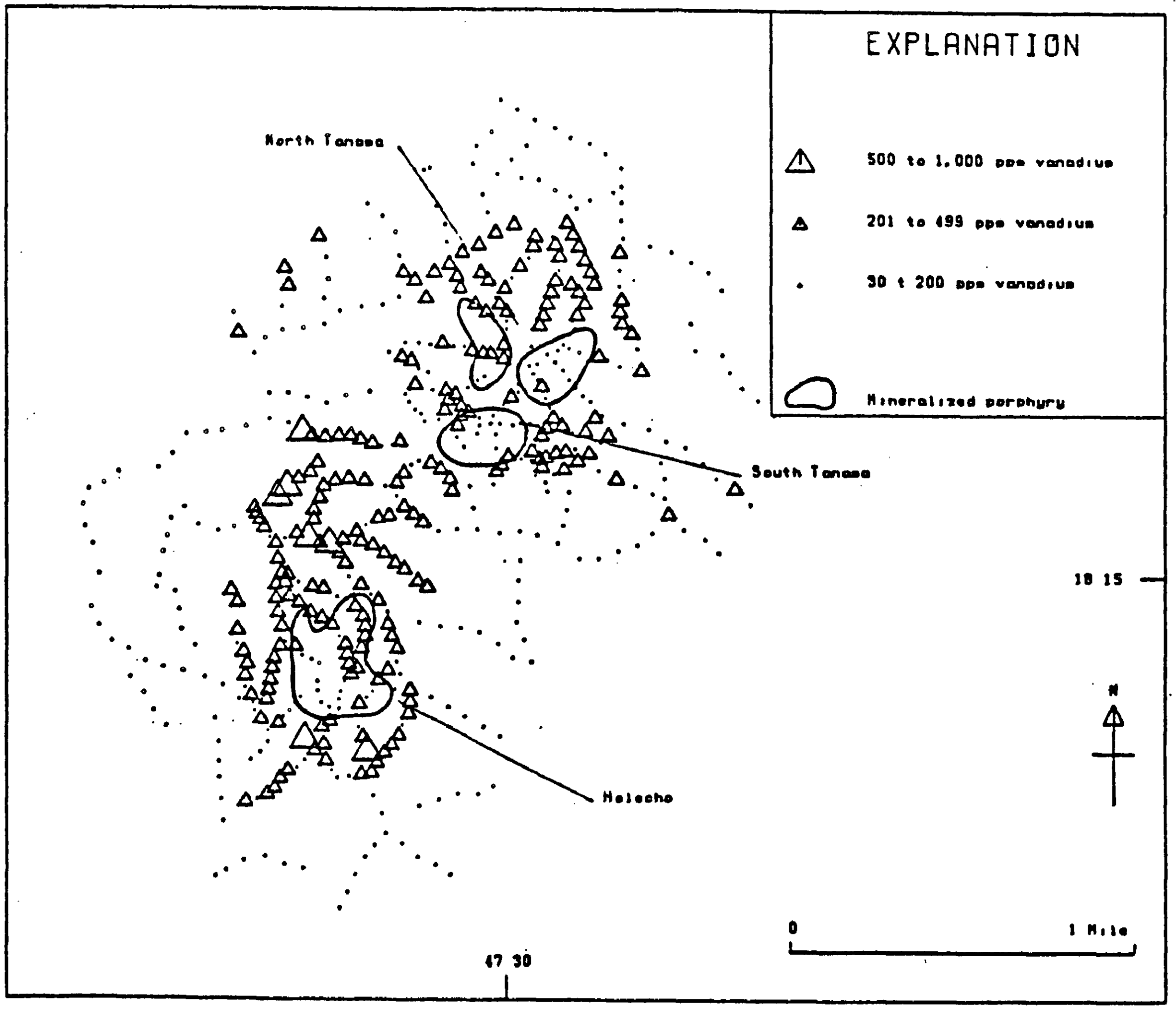

Figure 50. Distribution of vanadium in soil - Rio Tanama

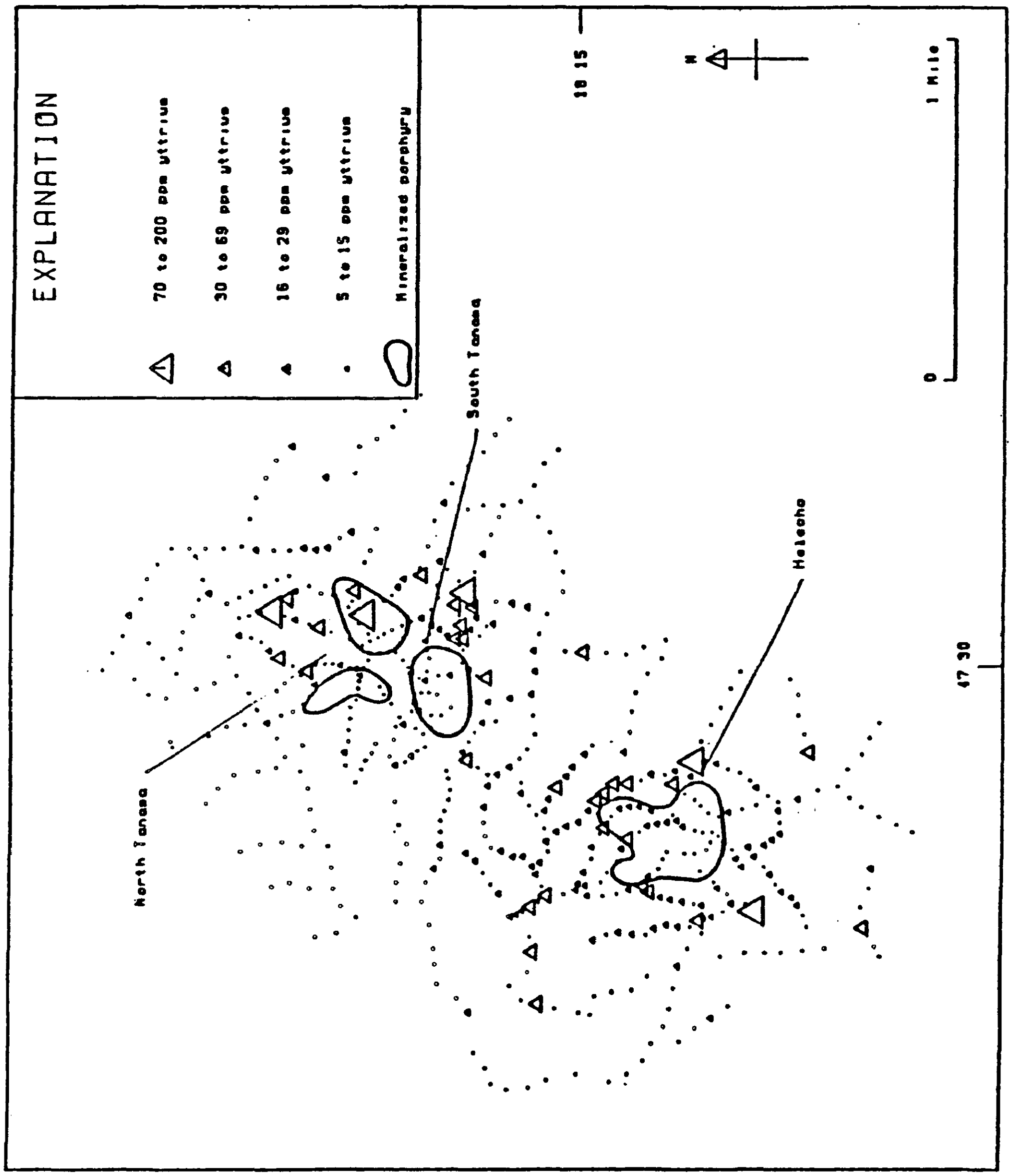

Figure 51. Distribution of yttrium in soil - Rio Tanama

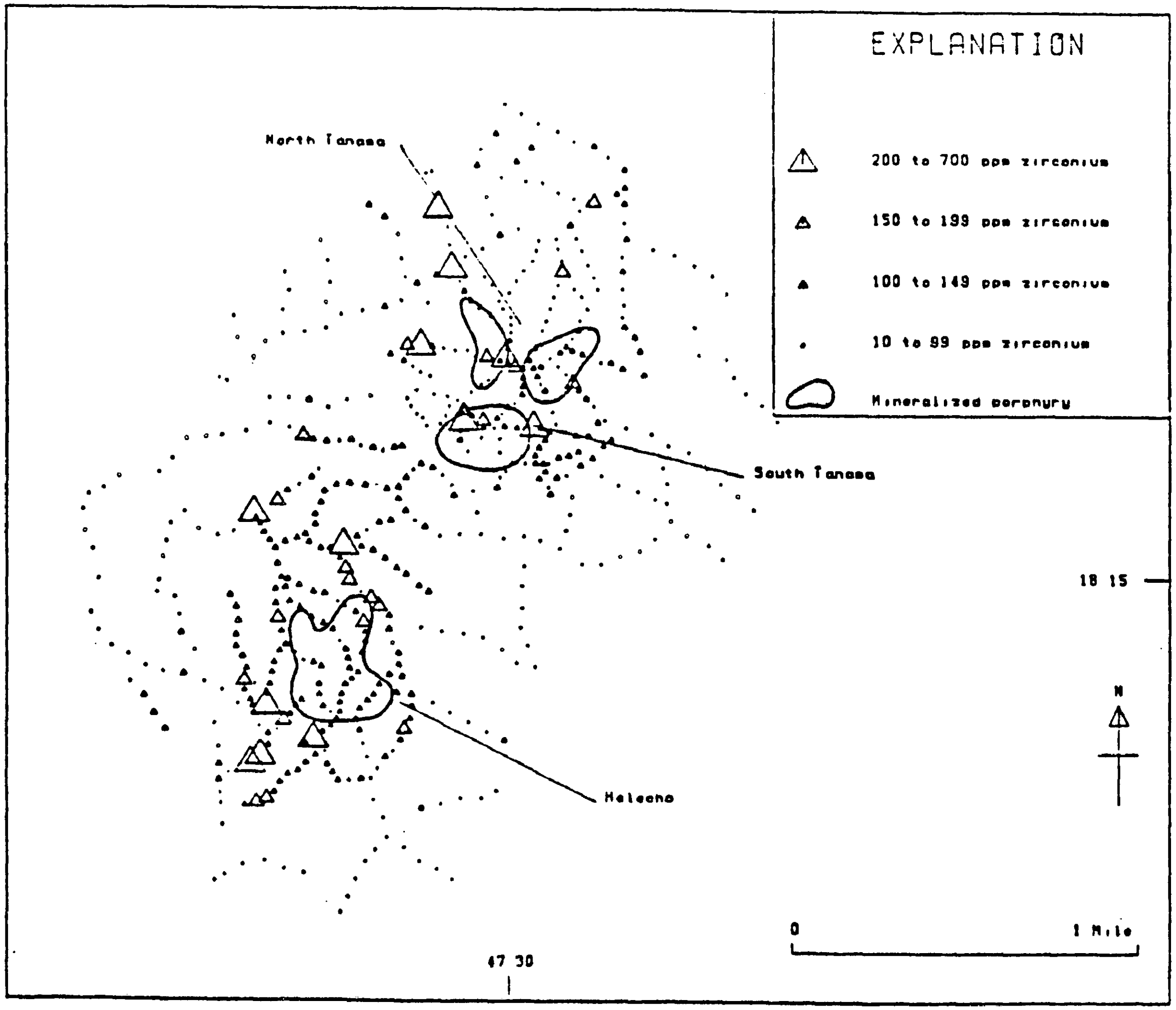

Figure 52. Distribution of zirconium in soil - Rio Tanama

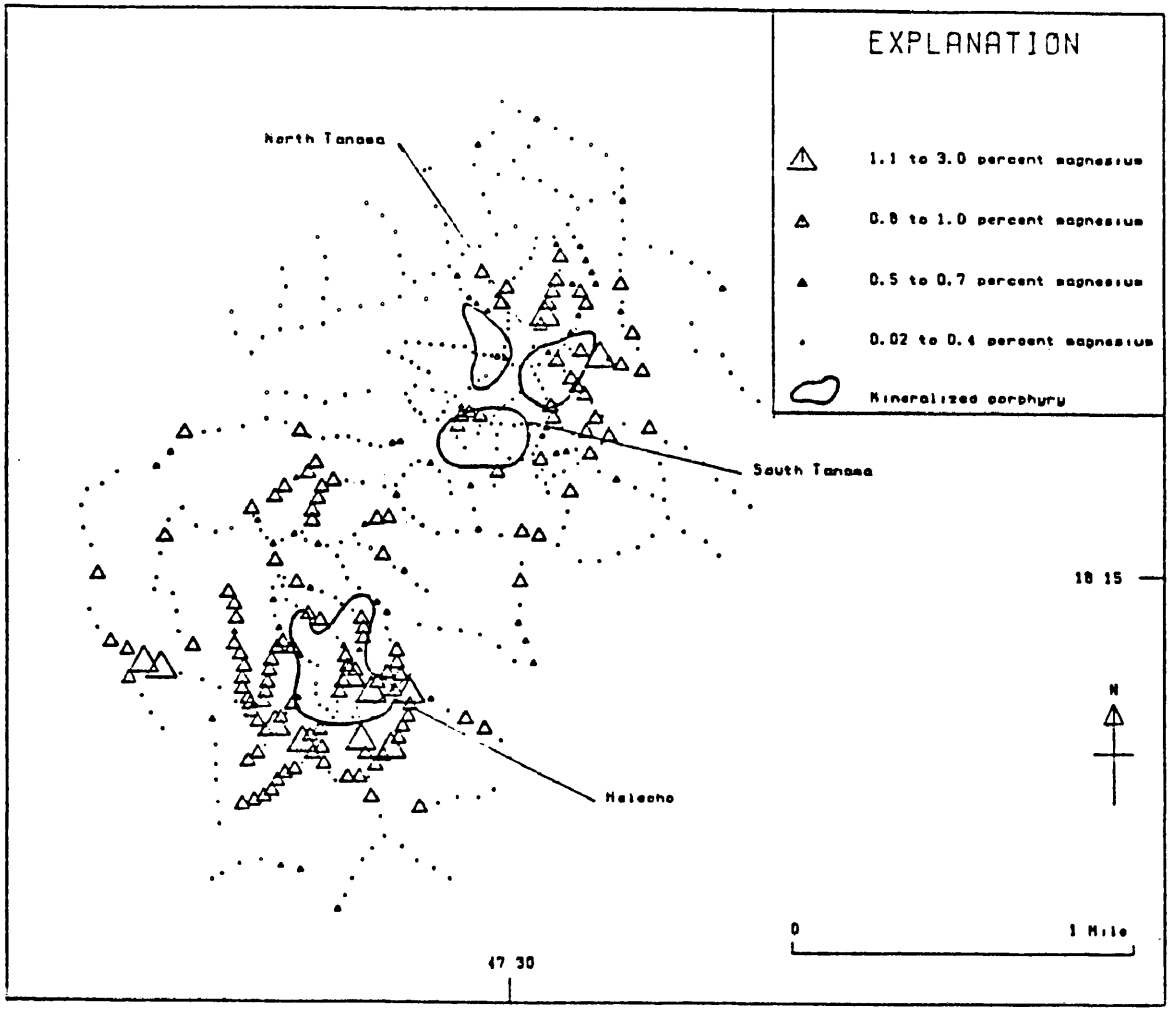

Figure 53. Distribution of magnesium in soil - Rio Tanama

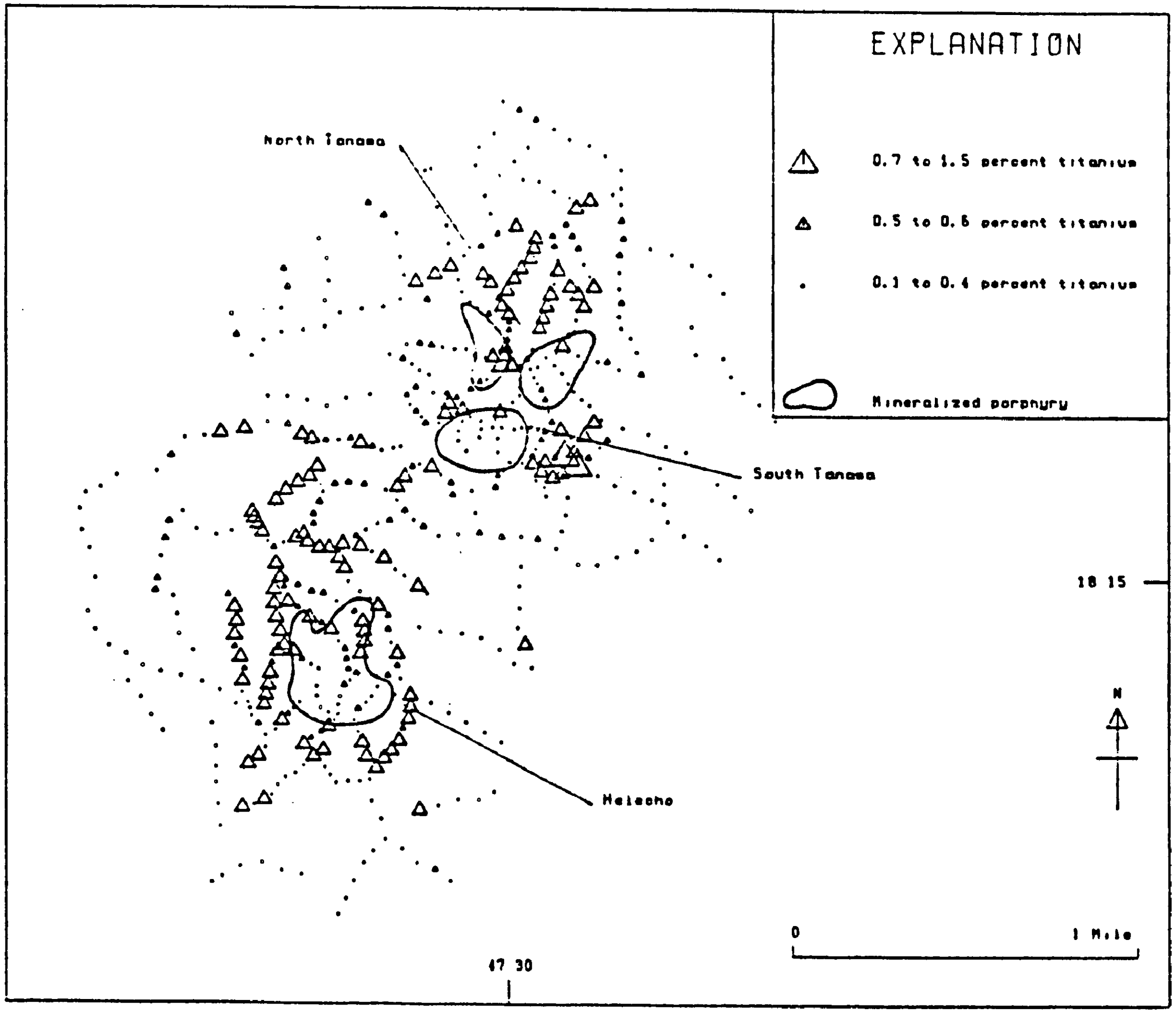

Figure 54. Distribution of titanium in soil - Rio Tanama