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NATURAL BACKGROUND GEOCHEMISTRY OF THE BANDELIER TUFF AND OTHER ROCK UNITS, LOS ALAMOS, NEW MEXICO

by

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ABSTRACT

Background elemental concentrations were determined for inorganic constituents of the Bandelier Tuff as part of Environmental Restoration investigations conducted at Los Alamos National Laboratory. A total of 251 bulk-rock samples was collected from outcrops across the Laboratory and borehole 49-2-700-1 at TA-49. Total elemental concentrations were determined for 208 samples by x-ray fluorescence and for 38 samples by instrumental neutron activation analyses to determine the chemical variability of rock units on the Pajarito Plateau. Then, based on the XRF and INAA results, a representative suite of 106 samples was selected for analyses by EPA SW846 methods for their leachable concentrations of inorganic analytes by inductively coupled plasma mass spectrometry, inductively coupled plasma emission spectroscopy, electrothermal vapor atomic absorption spectroscopy, or ion chromatography.

The Wilcoxon rank sum test and box plots were used to determine if there is a significant chemical difference between units of the Tshirege Member as well as between the Tshirege Member and other rock units. UTLs were calculated for all inorganic elements, except for iron and sulfate which have unusual distributions. The background screening value for inorganic analytes is the 95th percentile upper tolerance limit (UTL), which is the 95% upper confidence limit of the 95th percentile of the data distribution. For the elements that are normally distributed without any data transformation and the elements that are normally distributed after a square root transformation, UTLs were calculated using the following equation:

$$UTL_{0.95,0.95} = \text{mean} + \text{standard deviation} * k_{0.95,0.95}$$

The k-factor is dependent on the number of background samples. The UTLs for log normally distributed elements were estimated by a simulation process. The calculated UTL results were screened to ensure that the estimated UTLs were not artificially inflated due to a small sample size. Maximum detected concentrations were used to define background screening

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values for the rarely detected elements antimony, arsenic, chromium, copper, nickel, radium, silver, tantalum, and thallium as well as for iron and sulfate. Maximum concentrations are used to define background screening values for units Tt, Qbo, Qct, and Qbt 4 because they are represented by fewer than 10 samples. Background screening values for naturally occurring potassium, thorium, and uranium isotopes are calculated from total elemental concentration data.

The spatial coverage and population size of background chemistry samples are considered adequate for defining background screening values for units Qbt 1g, Qbt 1v, Qbt 2, and Qbt 3 of the Tshirege Member. These tuffs are the most widespread rock units on the Pajarito Plateau and make up the bedrock at the majority of the Laboratory's potential release sites. No additional background data are needed for these units. We recommend additional characterization of Qbt 4 because so few samples of this unit are included in the present data set. Preliminary background screening data are presented for pre-Tshirege rock units (tephras and volcaniclastic sediments of the Cerro Toledo interval, the upper part of the Otowi Member of the Bandelier Tuff, and dacitic lavas of the Tschicoma Formation); we recommend that these data be supplemented by local background data on an as needed basis.

INTRODUCTION

Background elemental concentrations were determined for inorganic constituents of the Bandelier Tuff as part of Environmental Restoration (ER) investigations conducted at Los Alamos National Laboratory (LANL). These background investigations conform with guidelines set forth in Task IV of the Laboratory's Hazardous and Solid Waste and Amendments (HSWA) permit to *"...describe the extent of contamination (qualitative/quantitative) in relation to the background levels indicative for the area"*. The background data supplements information from earlier background soil and tuff investigations by Longmire et al. (1995a) and the companion report to this study (Longmire et al., 1995b). These background data support Resource Conservation and Recovery Act (RCRA) investigations at the Laboratory and will be used as baseline data for RCRA facilities investigations (RFI). The data set provides regional coverage of the bedrock geologic units and can be used for identifying areas of contamination, performing baseline risk assessments, and planning remedial actions. The data can also be used to assess how local background data compares to regional background.

This report presents background chemical data primarily for the Tshirege Member of the Bandelier Tuff. The Tshirege Member is the most widespread rock unit on the Pajarito Plateau, and it is the bedrock unit at the majority of the Laboratory's potential release sites. The Tshirege data are considered complete except for unit 4. The western part of the Laboratory, where unit 4 is the major surface bedrock unit, was little characterized at the time samples were collected for stratigraphic studies of the Bandelier Tuff, and only 4 samples of this unit were available for background characterization. The presence of a thick sequence of unit 4 tuffs in borehole 49-2-700-1 at TA-49 was not discovered until after background samples were submitted for analysis of leachable inorganic analytes.

Additional background data are presented for some of the pre-Tshirege rock units including, in descending stratigraphic order: tephras and volcaniclastic sediments of the Cerro Toledo interval, the upper part of the Otowi Member of the Bandelier Tuff, and dacitic lavas of the Tschicoma Formation. Background data for the pre-Tshirege rock units are preliminary because of the low number of samples representing the units; however, these data provide useful bounding information on the geochemistry of these deeper units.

Two types of analytical data for inorganic constituents are presented in this report. *Leachable elemental concentrations* are provided to determine the bioavailabilty of elements for risk assessment calculations. Leachable elemental concentrations were determined by first leaching the loosely bound inorganic constituents of the rocks in a water or acid solution, and then analyzing the leachate. The leachable elemental concentrations are the primary focus of this report because RFI soils and rocks also are analyzed for their leachable elemental concentrations.

Total elemental concentrations also are discussed in this report and refer to the total concentration of an inorganic element in a rock, including the insoluble forms of the elements tightly bound in mineral structures as well as acid leachable (bioavailable) forms. Total elemental concentrations provide important information about: (1) the natural geochemical variability of the rock units, (2) the leachability behavior of inorganic constituents in different geologic settings, (3) discrimination of contaminated vs. uncontaminated media, and (4) geochemical processes controlling contaminant transport. In addition, background screening values for naturally occurring potassium, thorium, and uranium isotopes are calculated from total elemental concentration data. Data for total elemental concentrations are presented graphically, and comparisons between leachable elemental concentrations and total elemental concentrations are made on an analyte by analyte basis. The total elemental concentrations are not treated statistically and are used as supporting data for understanding the distribution of inorganic elements in the rock units.

This report summarizes the results of background chemistry investigations for rocks of the Pajarito Plateau. Field, analytical, and statistical methods used to describe background element concentrations are described, and geologic factors that control elemental distributions are discussed. Background elemental values are determined for each rock unit, and background screening values are calculated based on upper threshold limits or maximum reported concentrations. The data are summarized in tables and figures, and the underlying data will be available through the Facility for Information Management and Display (FIMAD).

METHODS

A total of 251 bulk-rock samples was collected from rock units across the Pajarito Plateau. One hundred and eighty-seven of the samples were collected from outcrops as part of stratigraphic studies of the Bandelier Tuff and older units, and details about sample collection as well as other relevant information about the geologic setting of the samples are given elsewhere (Broxton et al., 1995a, 1995b, 1995c; Longmire, 1995a). Sixty four samples were collected from background geology borehole 49-2-700-1 at TA-49 (Stimac et al., 1995). Areas where samples were collected are shown in Fig. 1.

In general, field work was performed using the procedure Characterization of Lithologic Variations within the Rock Outcrops of a Volcanic Field (LANL-ER-SOP-03.07). Typically, samples were collected in vertical stratigraphic sections at a nominal vertical spacing of 5 m or at major changes in lithology. Metal tags mark sample sites in the field. Vertical control was maintained by Jacob staff and Abney level in the field, and locations and elevations were estimated from maps or were surveyed by a professional surveying company. Site observations generally included descriptions of rock type, unit thickness, type and degree of alteration, welding and compaction, phenocryst assemblage and abundance, color of fresh and weathered surfaces, pumice size and abundance, and weathering characteristics. Bedding characteristics, fractures and their filling materials, and lithic assemblage, size, and abundance were also noted.

Table I summarizes the analytical methods, analytes, and numbers of samples collected in this study. First, total elemental concentrations were determined for 208 samples by x-ray fluorescence (XRF) and 38 samples by instrumental neutron activation analyses (INAA) to determine the chemical variability of rock units on the Pajarito Plateau. Then, based on the XRF and INAA results, a representative suite of 106 samples was selected for analyses by EPA SW846 methods for their leachable concentrations of inorganic analytes. These included 5 outcrop samples from the Tschicoma Formation that were analyzed only for their inorganic analytes.

SW846 leachable elemental concentrations were determined by inductively coupled plasma mass spectrometry (ICPMS), inductively coupled plasma emission spectroscopy (ICPES), and electrothermal vapor atomic absorption spectroscopy (ETVAA). Aliquots of crushed rock powders were treated with a solution of concentrated HNO_3 (pH<1), and the leachate was analyzed by ICPMS and ICPES. Separate aliquots of crushed rock powders were treated with de-ionized water and the leachate was analyzed for chlorine and sulfate by ion chromatography (IC). Thirteen untreated samples were analyzed for Radium-226 activities by gamma-ray spectroscopy (G).

Total elemental concentrations were made using an automated Rigaku wavelength-dispersive X-ray fluorescence (XRF) spectrometer located in the Geology/Geochemistry Group (EES-1) at LANL. Details about XRF analytical conditions are summarized in Broxton et al. (1995b, 1995c). Total elemental concentrations by INAA (Table I) were performed at the Omega West reactor facility at LANL. Minor et al. (1982) and Garcia et al. (1982) provide additional infor-

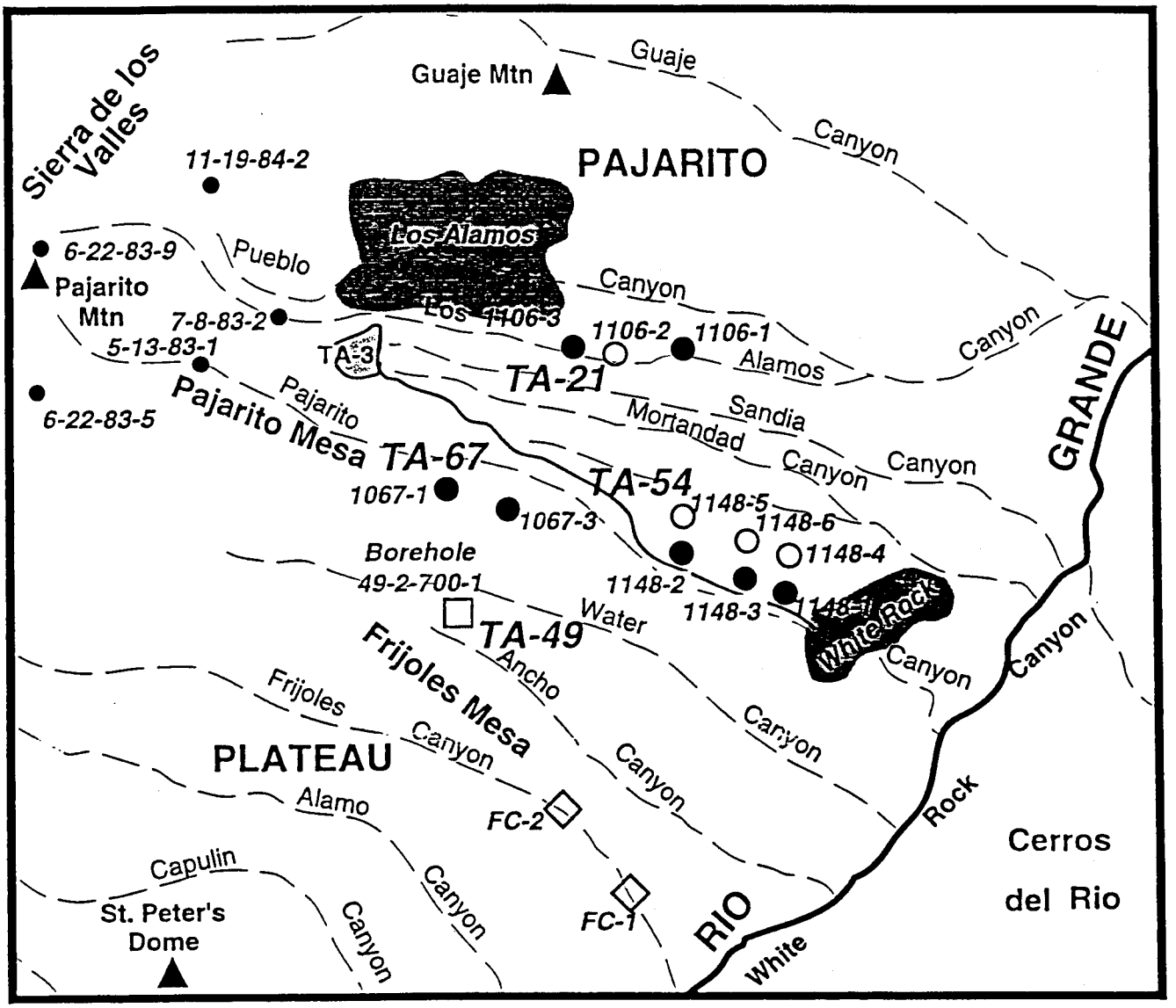


Fig. 1. Map showing location of sites where background chemistry samples were collected from outcrops and a borehole. Large filled circles indicate sites of outcrop samples that were analyzed for both leachable and total elemental concentrations. Open circles are sites of outcrop samples analyzed for total elemental concentrations by XRF only. Open diamonds are sites of Frijoles Canyon outcrop samples analyzed for total elemental concentrations by INAA only. Small filled circles are outcrop sites where samples of the Tschicoma Formation were sampled and analyzed for leachable elemental concentrations. The name of the stratigraphic sections are shown in italics next to the symbols described above. Borehole 49-2-700-1 at TA-49 (open box) was also sampled, and total elemental concentrations were determined by XRF.

mation about analytical uncertainties, conditions of analysis, and detection limits for elements analyzed by INAA. Total radium was determined for 13 samples by gamma-ray spectrometry. Loss on ignition (LOI) was determined by measuring the difference in sample weight at room temperature and after heating at 1000°C for one hour.

TABLE I.

ANALYTES, ANALYTICAL METHODS, AND NUMBERS OF SAMPLES FOR BACKGROUND CHEMISTRY INVESTIGATION OF ROCK UNITS ON THE PAJARITO PLATEAU

	Leachate Analyses				Total Rock Analyses			
Analysis Method	ICPES	ICPMS	IC	ETVAA	G	XRF	INAA	
Number of Analyses	106	106	106	106	13	208	38	
Analytes	Ag	Pb	SO4	As	Ra	Si	Na	Sb
	Al	Sb	Cl			Ti	Mg	I
	Ba	Ta				Al	Al	Cs
	Be	Th				Fe	Cl	Ba
	Ca	Tl				Mn	K	La
	Co	U				Mg	Ca	Ce
	Cr					Na	Sc	Nd
	Cu					K	Ti	Sm
	Fe					P	V	Eu
	K					V	Cr	Tb
	Mg					Cr	Mn	Dy
	Mn					Ni	Fe	Yb
	Na					Zn	Co	Lu
	Ni					Rb	Cu	Hf
	V					Sr	Zn	Ta
	Zn					Y	Ga	W
						Zr	As	Au
						Nb	Se	Hg
						Ba	Br	Th
							Rb	U
							Sr	Be
							Zr	Cd
							Ag	Pb
							In	

GEOLOGIC SETTING

The stratigraphic nomenclature for the Bandelier Tuff used in this investigation follows the usage of Broxton and Reneau (1995). Figure 2 shows the stratigraphic relations of the units discussed, and Figure 3 shows Bandelier Tuff nomenclature as used in other Laboratory reports dating back to the early 1960s. In descending stratigraphic order, the rock units represented in this background study include: the Tshirege Member of the Bandelier Tuff, tephras and volcaniclastic sediments of the Cerro Toledo interval, the upper part of the Otowi Member of the Bandelier Tuff, and dacitic lavas of the Tschicoma Formation.

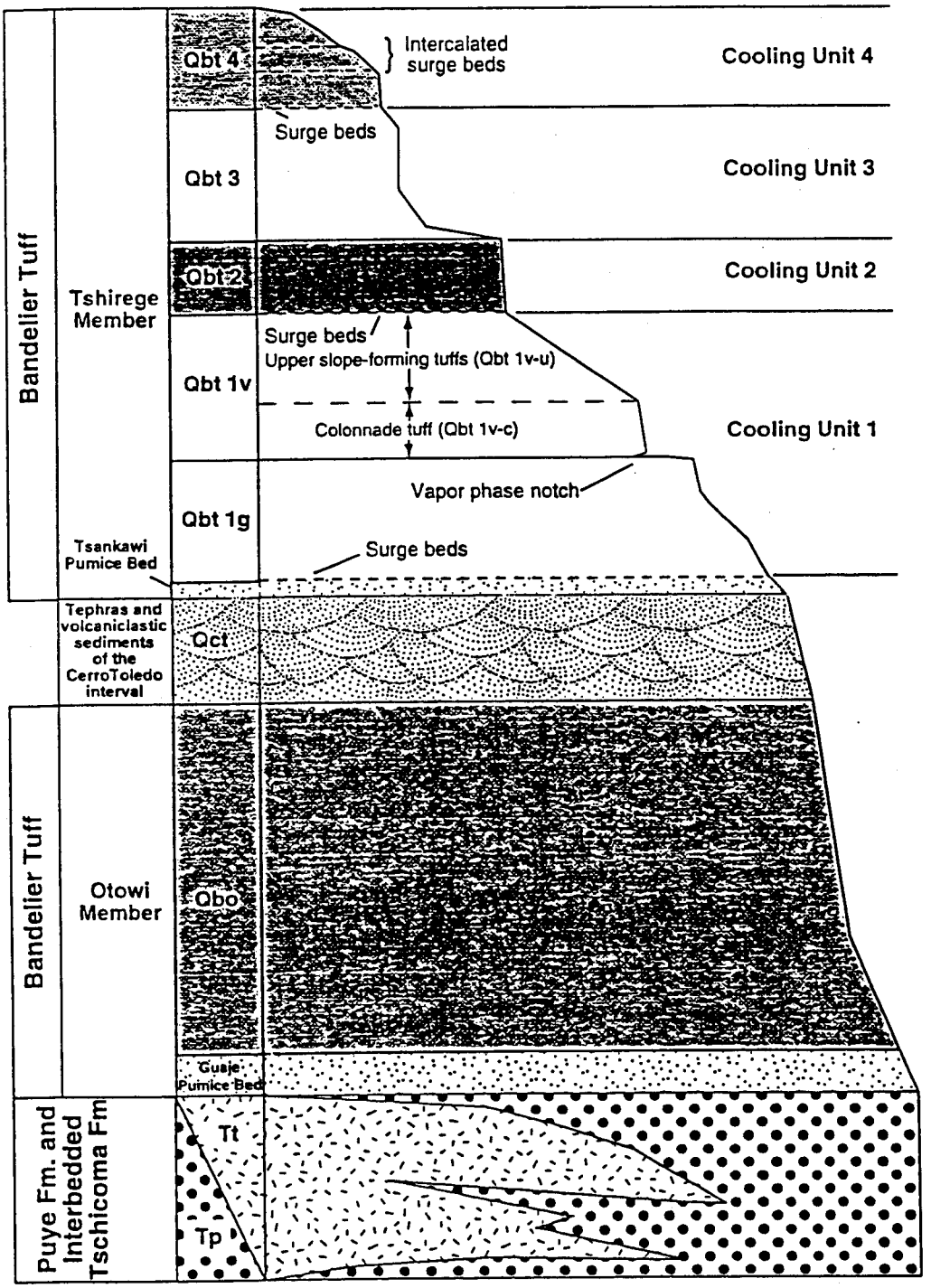


Fig. 2 Schematic stratigraphic section showing rock units sampled for background chemistry. Modified from Broxton and Reneau (1995).

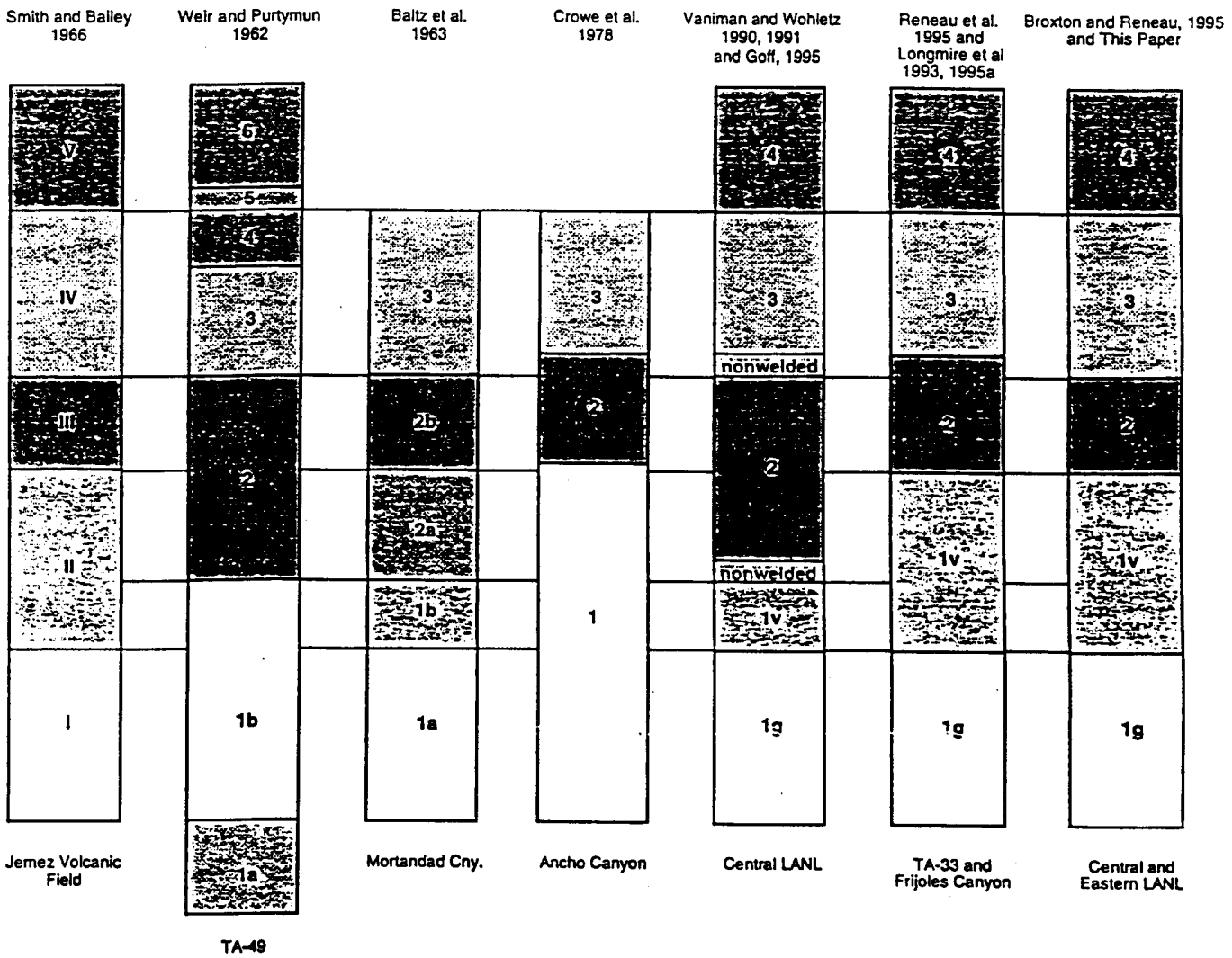


Fig. 3 Chart showing correlation of rock unit names applied to the Tshirege Member of the Bandelier Tuff by various investigators. From Broxton and Reneau (1995).

The Tshirege Member is a thick ignimbrite sheet that was erupted from the Valles caldera 1.21 Ma (Smith, 1960; Smith and Bailey, 1968, Izett and Obradovich, 1994). Because of its complex cooling history, the Tshirege Member forms a compound cooling unit divided into the basal Tsankawi Pumice Bed and four overlying ignimbrite cooling units. Consequently, the physical properties of the Tshirege Member vary both vertically and laterally. The lower three cooling units crop out in the central and eastern part of the Laboratory, and the fourth is present only in the western part. These cooling units, labeled 1 through 4 in ascending order (Fig. 2), represent episodes of ash-flow deposition that were separated by partial cooling breaks.

The Tshirege Member is a chemically zoned ignimbrite sheet, and the concentrations of minor and trace elements vary with stratigraphic height above the base of the unit. Chemical zonations in the Tshirege Member represent the compositional zonations that existed in the Bandelier

magma chamber before eruption (Smith and Bailey, 1968; Smith, 1979). The earliest erupted magmas mainly tapped the top of the magma body and were deposited as the stratigraphically lowest ignimbrites. Further eruptions continued to draw down the magma body, tapping generally deeper compositional zones of the magma body; these later eruptions resulted in the deposition of stratigraphically higher parts of the Tshirege ignimbrite sheet. Thus the chemical zonation in the Tshirege Member represents in inverted order the general compositional zonation of the Tshirege magma chamber before eruption, although some mixing of different levels of magma occurred during in each eruptive event.

Tephras and volcaniclastic sediments of the Cerro Toledo interval is an informal name given to a sequence of epiclastic sediments and tephras of mixed provenance that lies between the two members of the Bandelier Tuff (Broxton and Reneau, 1995). The age of this unit is bracketed by the ages of the Tshirege and Otowi Members (1.22-1.61 Ma; Izett and Obradovich, 1994). This unit contains some deposits normally assigned to the Cerro Toledo Rhyolite, including tuffaceous sandstones and siltstones and primary ash-fall and pumice-fall deposits (Smith et al., 1970; Heiken et al., 1986). The Cerro Toledo interval also includes poorly sorted coarse-grained volcaniclastic sediments derived from lava flows of the Tschicoma Formation. In most cases, both types of volcaniclastic deposits are intercalated, and it is not practical to separate them. Samples for this investigation were collected only from primary fallout deposits. This allowed us to characterize one end-member (high-silica rhyolite tuffaceous material) within this complex assemblage. The other end member composition is represented by analyses from the dacitic lavas of the Tschicoma Formation, which are described below.

The Otowi Member of the Bandelier Tuff is a relatively homogenous unit made up of a succession of ignimbrites. The ignimbrites are nonwelded to partially welded in the areas studied, and the entire sequence of tuffs apparently forms a simple cooling unit. Only the upper part of the Otowi Member was accessible at the sites studied, therefore the elemental data presented los Valles. Tschicoma Formation rocks represent end member compositions for the gravel component of stream-transported sediments in these larger drainage systems. These Tschicoma-derived stream sediments and soils Bandelier Tuff as the streams cross the Pajarito Plateau.

STATISTICAL APPROACH

Statistical Analysis of Bandelier Tuff and Other Geologic Units

The goal of the statistical analysis of the background tuff data is to develop a technically defensible set of data for Environmental Restoration (ER) Project decision-making. The key to technical defensibility is ensuring that the rock analyses represent the natural variation found within each of the Laboratory's geological rock units. Thus the background rock samples were collected from areas that were not affected by Laboratory operations.

The background data are used to support the RFI screening process ("Screening Assessment Methodology at Los Alamos National Laboratory", LANL ER Project, January 1995, draft). As a part of the RFI process, data for most sites are compared to natural background concentration of inorganic analytes. The screening action level (SAL) comparison step fol-

lows the background comparison in the screening assessment process. The SALs cited in this report are based on EPA Region 9 Preliminary Remediation Goals (PRGs). The background screening value for inorganic analytes is the 95th percentile upper tolerance limit (UTL), which is the 95% upper confidence limit of the 95th percentile of the data distribution. The type of data distribution for each inorganic analyte must be estimated to calculate these UTLs.

The statistical analysis of the background data is a step-wise process involving the following steps:

a) determine if there is a significant chemical difference between units of the Tshirege Member as well as between the Tshirege Member and other rock units.

b) estimate the type of data distribution for each inorganic analyte so that UTLs can be calculated.

c) calculate background screening values for each analyte by stratigraphic unit using either UTLs or the maximum reported values for infrequently detected analytes or sparsely sampled stratigraphic units.

Initial Data Analysis Steps

Some of the inorganic results in the combined background rock data set are reported as less than the detection level (<DL). To facilitate statistical analysis of the data, all values reported as <DL were replaced by one-half of the detection limit. This replacement approach is recommended in the EPA risk assessment guidance (EPA 1992, 1166). Concentrations below detection limits commonly occurred for antimony, arsenic, chromium, copper, nickel, radium, silver, tantalum, and thallium. These analytes are excluded from further statistical analyses.

Three samples (field sample numbers 1106-3-12, 1106-3-13, and 1106-3-14) from the Tshirege Qbt 1g/Qbt 1v contact from a stratigraphic section at TA-21 were excluded from the statistical analyses of these two units. This contact, which coincides with a feature called the vapor-phase notch (Broxton et al., 1995), contains anomalous elemental concentrations that significantly skew some statistical parameters when included with the data sets for these units. Exclusion of the samples is justified because they represent a relatively thin zone (~2 m) of chemical alteration specific to the vapor phase notch at one locality, and they are not representative of the chemical characteristics of units 1g and 1v as a whole.

Comparison of Units of the Tshirege Member as well as between the Tshirege Member and other rock units

The statistical analyses first compared rock units represented by 10 or more samples. Because of the sampling bias which focused this study on the Tshirege Member, only units of the Tshirege Member are represented by 10 or more samples. These units included unit 1g (Qbt 1g), unit 1v (Qbt 1v), unit 2 (Qbt 2), and unit 3 (Qbt 3) (Fig. 4). The box plots show the actual values (as filled circles) for each stratigraphic unit. The ends of the box represent the "inter-

quartile" range of the data distribution. The inter-quartile range is specified by the 25th percentile and 75th percentile of the data distribution. The line within the box plot is the median (50th percentile) of the data distribution. Thus the box indicates concentration values for the central half of the data, and concentration shifts can be readily assessed by comparing the boxes. If the majority of the data is represented by a single concentration value (usually the detection limit), the box is reduced to a single line. The solid line spanning the series of box plots is the mean value for the entire data set. Unit 4 (Qbt 4) of the Tshirege Member, tephras and volcaniclastic sediments of the Cerro Toledo interval (Qct), the Otowi Member (Qbo) of the Bandelier Tuff, and the Tschicoma Formation (Tt) were represented by fewer than ten samples and were excluded from the statistical comparisons. Background screening values were developed from the maximum observed value in Qbt 4, Qct, Qbo, and Tt.

Units 1g, 1v, 2, and 3 of the Tshirege Member were statistically compared by the Wilcoxon rank sum test. The Wilcoxon rank sum test is one of the "distribution shift" methods discussed in the LANL ER Project Policy Paper on background comparisons (Environmental Restoration Project Assessments Council 1995, 1218). The statistical comparisons were conducted in a stepwise manner to be consistent with the geological relationships between these rock units. The first step involves a test for a statistically significant difference between units Qbt 1g and Qbt 1v. If these units were not statistically different, these data were lumped in a single data group (Qbt 1), and subsequent statistical comparisons were made between the pooled Qbt 1 data and the other Tshirege units. If Qbt 1g and Qbt 1v were significantly different, we compared each of these units separately to the other Tshirege units.

Estimating Data Distributions for Bandelier Tuff Background Data

The distribution properties of the rock units were summarized, and the results are presented in the Results and Discussion. The visual data displays presented by box plots were used to assign Tshirege unit results to data groups. Statistical distributions that best model the data were used to calculate the UTLs.

Calculation of Background Screening Values for Bandelier Tuff and Other Geologic Units

UTLs were calculated for all inorganic elements, except for iron and sulfate, where enough values were detected to allow estimation of the statistical distribution. Iron and sulfate have unusual distributions, which do not allow use of a simple statistical distribution model. Therefore, we propose use of the maximum detected value as a background screening value for iron and sulfate as well as for the rarely detected elements (antimony, arsenic, chromium, copper, nickel, radium, silver, tantalum, and thallium).

For the elements that are normally distributed without any data transformation and the elements that are normally distributed after a square root transformation[1], we calculated parametric tolerance limits by using the following equation:

$$UTL_{0.95,0.95} = \text{mean} + \text{standard deviation} * k_{0.95,0.95}{}^{1}$$

[1] *For square root transformed data, the UTL is calculated from the mean and standard deviation of the transformed data, and the resulting estimate of the UTL is squared to facilitate comparisons to site results.*

The k-factor depends on the number of background samples; complete tables of k-factors are published in the RCRA ground water statistical analysis document (EPA 1989, 1141) and Gilbert (1987, 0312). Readers are referred to the LANL ER Project policy paper on background comparisons for example k-factors.

The UTLs for log normally distributed elements were estimated by a simulation process. These simulations were run in the S-plus statistical programming environment. The S-plus code is presented in Appendix I. These simulations were run for 10,000 trials, which were sufficient to estimate the lognormal UTLs to two to three significant digits.

The raw calculated UTL results were screened to ensure that the estimated UTLs were not artificially inflated due to a small sample size.

We compared the relative value of the median, mean and calculated UTLs for the cooling unit subgroups and the overall combined background data set. If the mean and the median for a cooling unit were less than the combined data set mean or median and the UTL for the subset was greater than the combined data set, we substituted the overall data UTL for the unit subgroup UTL. We propose that these trimmed UTL values, and the sample maximum for the analytes discussed above, be used as the LANL-wide background screening values.

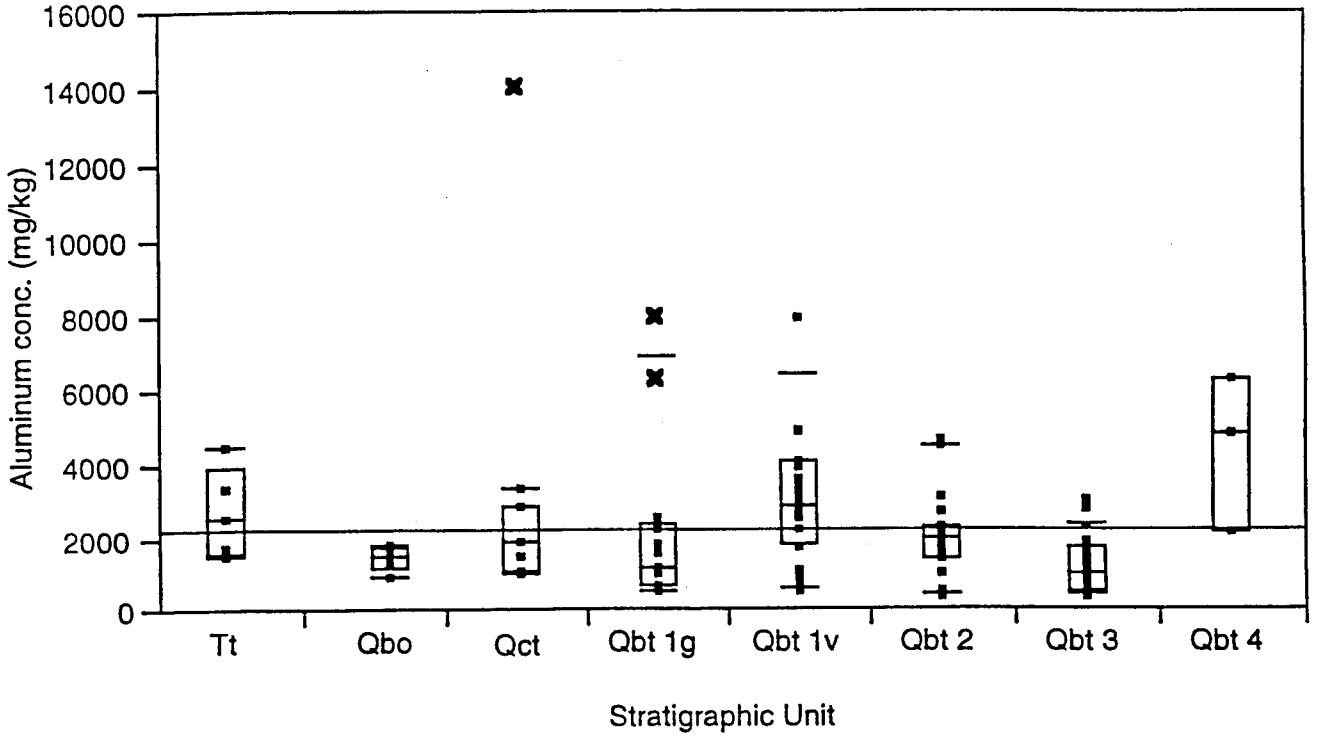
RESULTS AND DISCUSSION

Table II summarizes the detection limits, number of samples above and below detection limits, and the minimum, maximum, and mean value of samples above detection limits for all leachable inorganic analytes. Box plot summaries of all leachable inorganic analytes by rock units are presented in Figure 4, and samples ranges for these analytes are summarized in Table III.

The significance levels for the pairwise Wilcoxon rank sum test are presented in Table IV. Four inorganic analytes (barium, beryllium, lead and sulfate) showed no consistent statistical difference between the cooling units. The data for these analytes were collapsed into one group Qbt 123, and the remaining statistical analyses were performed on this single data group. All other analytes were partitioned into two, three or four data groups based on the results of the Wilcoxon rank sum test, and the remaining statistical analyses were performed on these data subgroups.

Table V summarizes the distribution properties of the Bandelier Tuff inorganic analytes. Distributions were either normally distributed or were transformed to normality with either a log- or square root transformation.

The raw calculated UTLs for inorganic constituents are presented in Table VI and the summary of background screening values (trimmed UTL values or strata maximums) is presented in Table VII. Trimmed UTL values or strata maximums should be used as the LANL-wide background screening values for the Bandelier Tuff units Qbt 1, Qbt 2 or Qbt 3. Maximum concentrations are used to define background screening values for units Tt, Qbo, Qct, and Qbt 4 because they are represented by fewer than 10 samples.



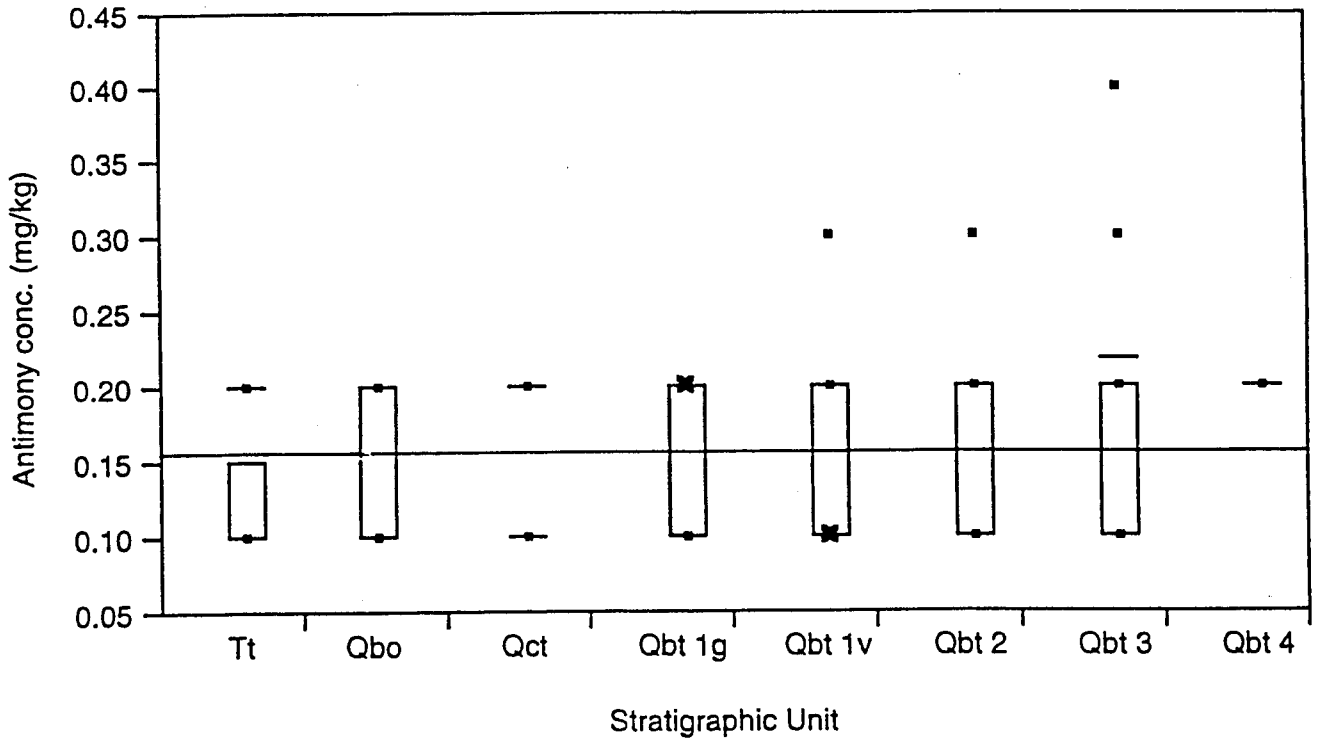
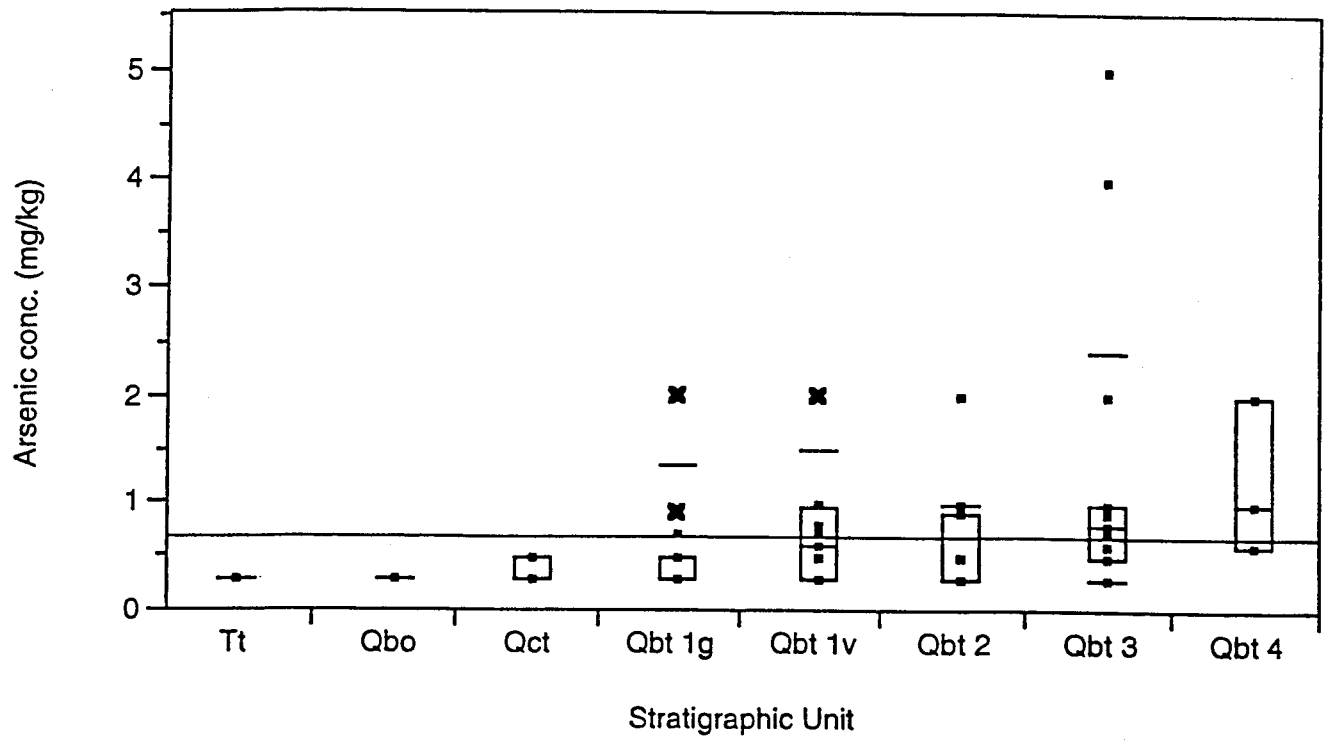
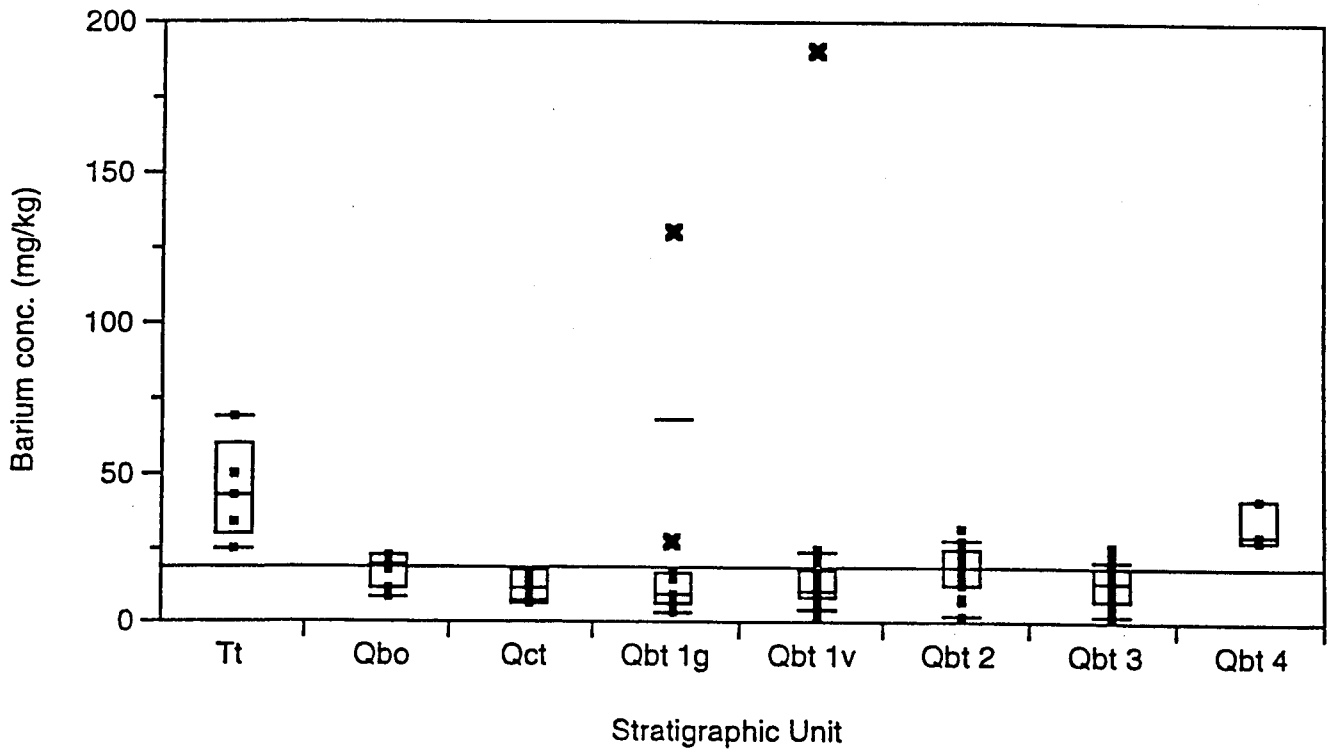


Fig. 4 Box plot summaries of leachable inorganic analytes by geologic unit. See Figure 2 for explanation of geologic unit labels. Explanation of box plots symbols is given in the text. The "x" values in these plots are vapor phase notch samples from stratigraphic section 3 at TA-21.





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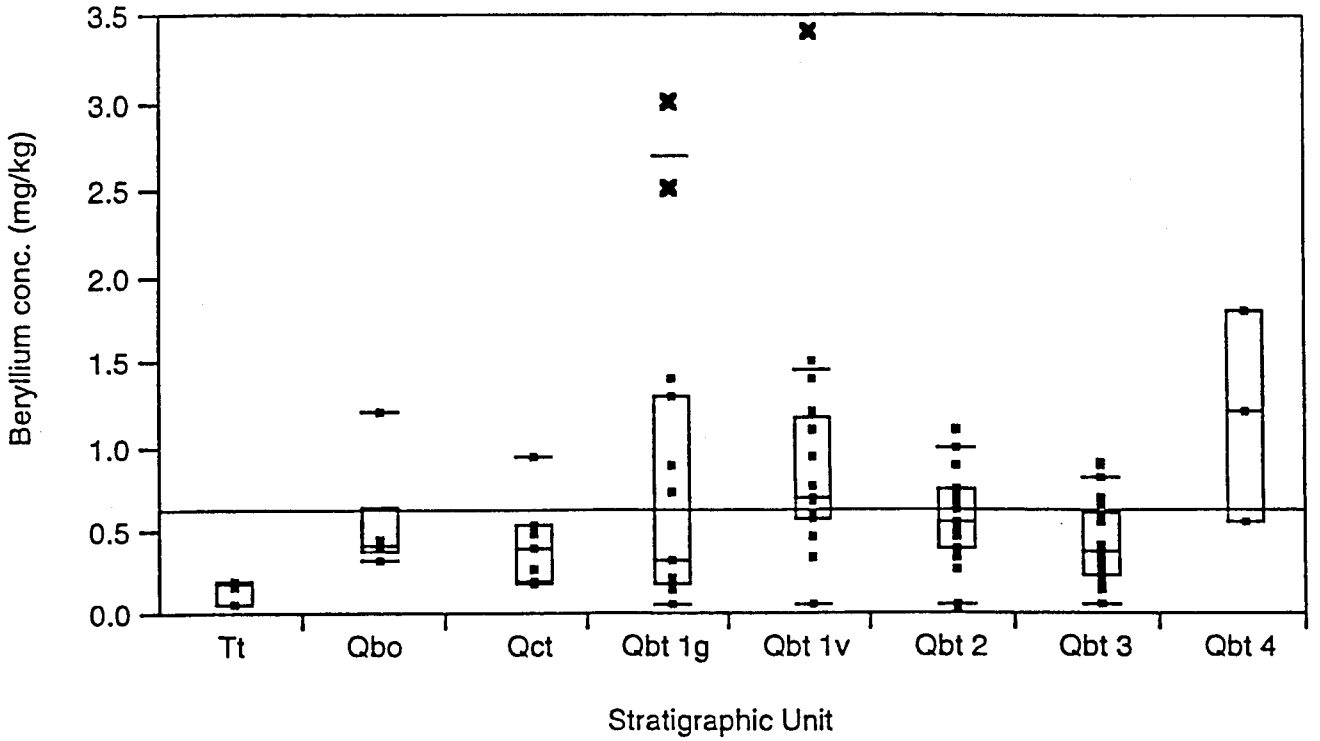

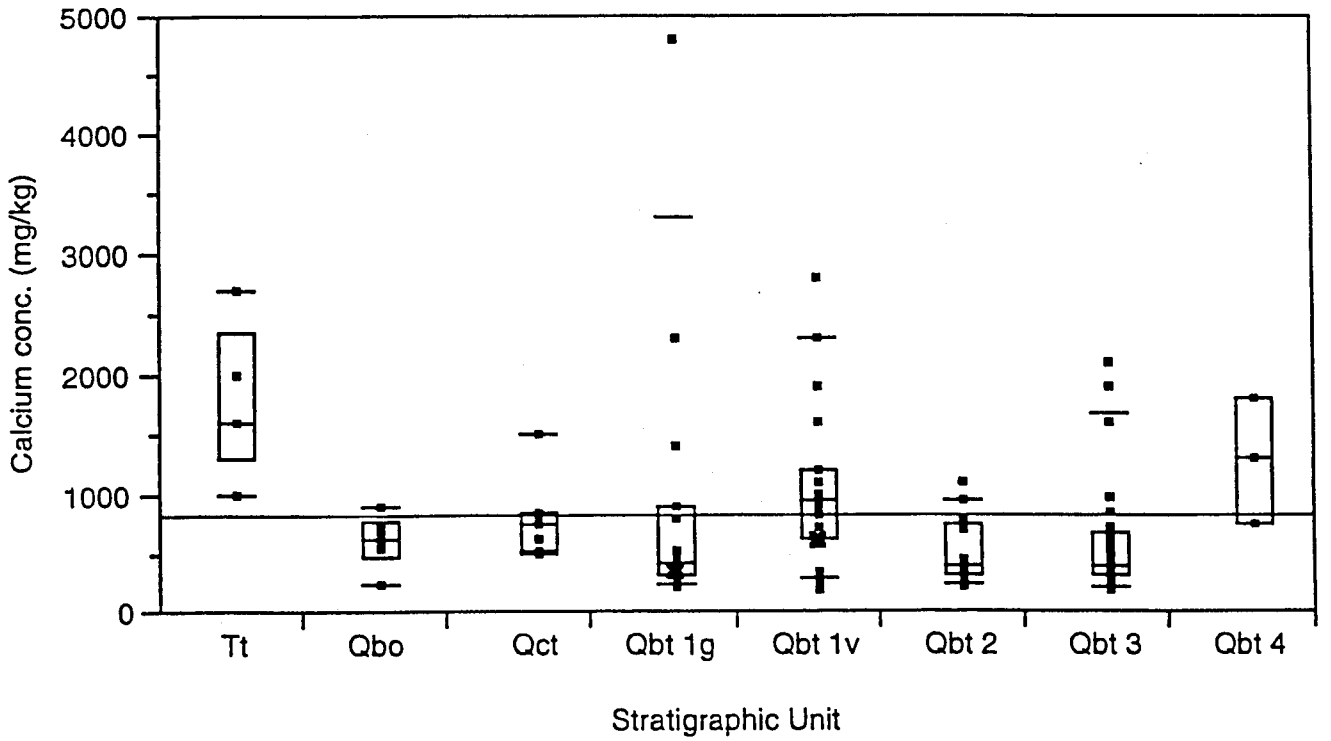

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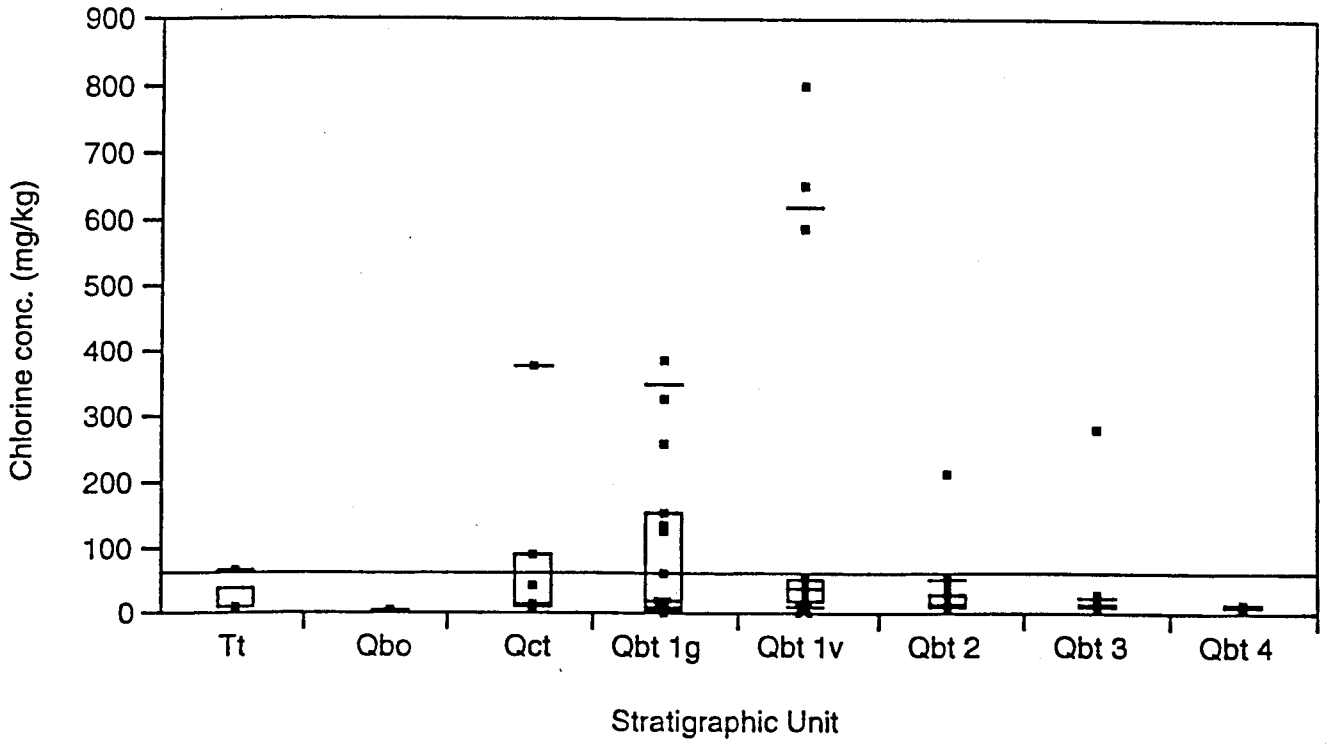

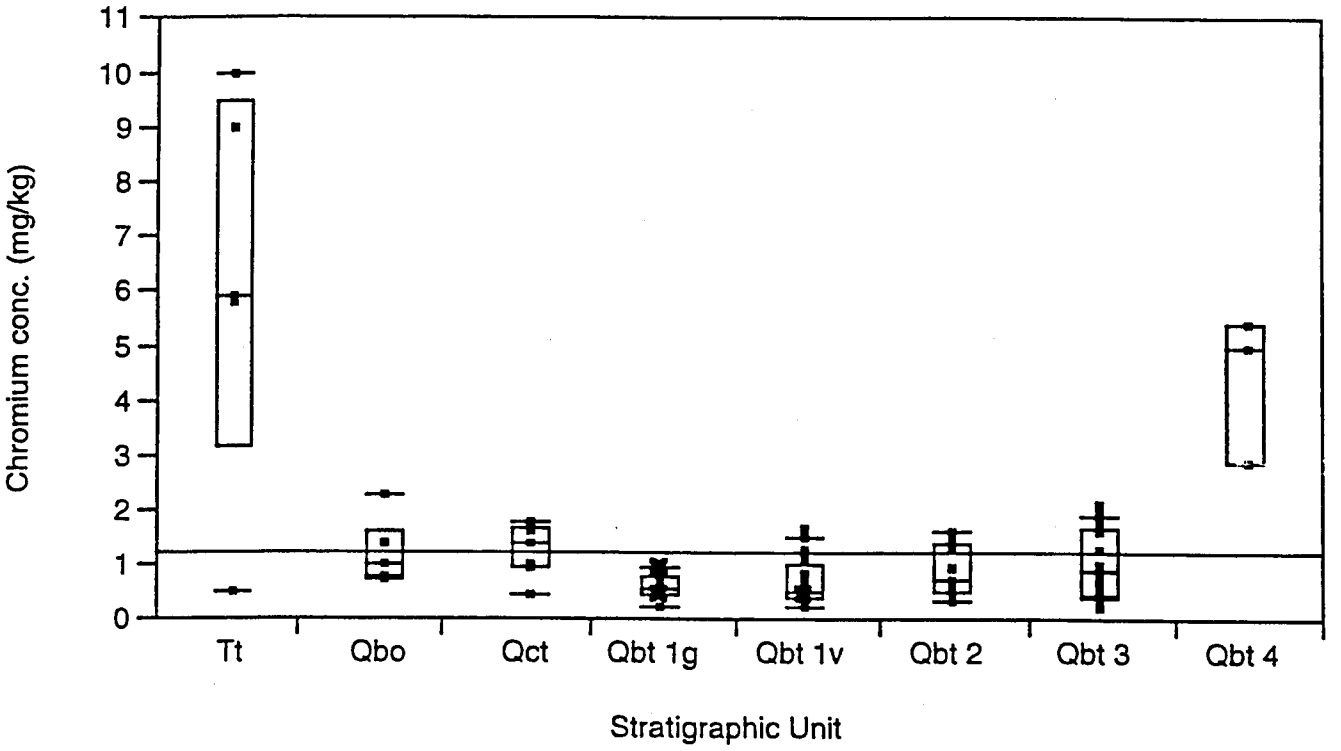

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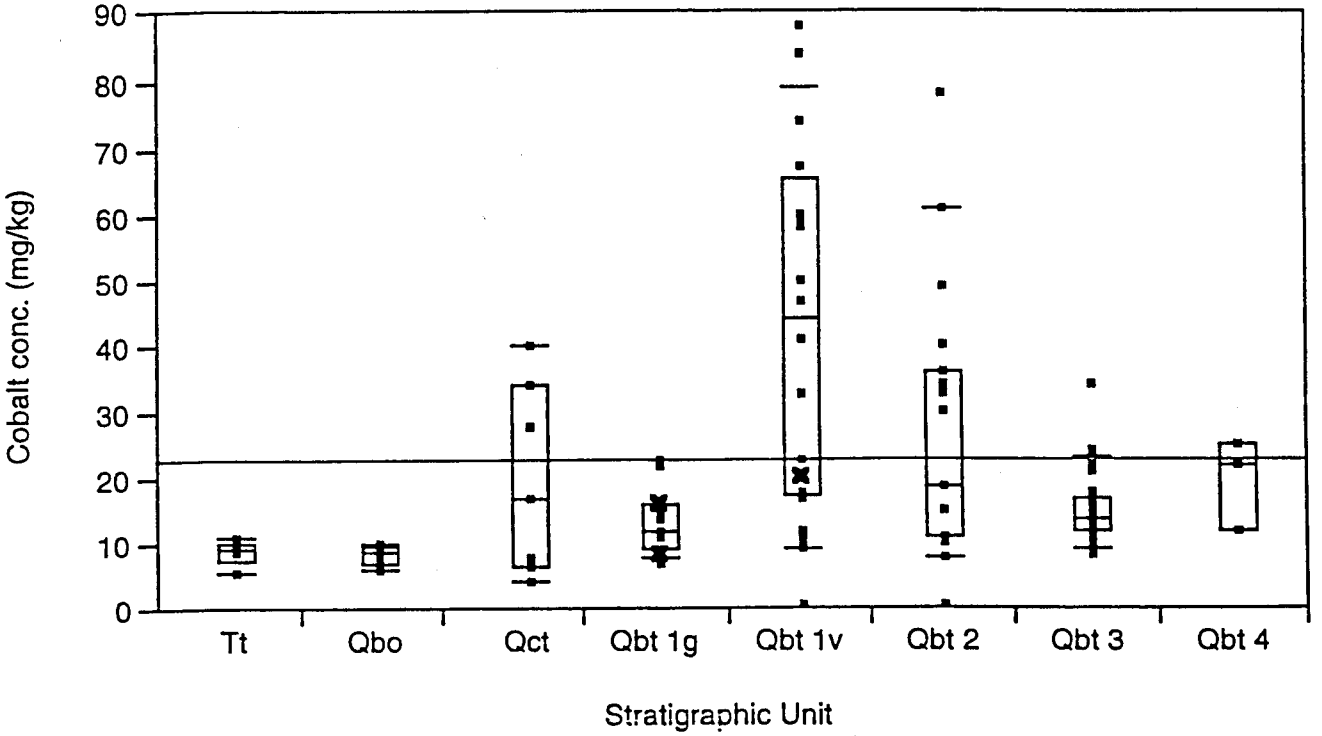


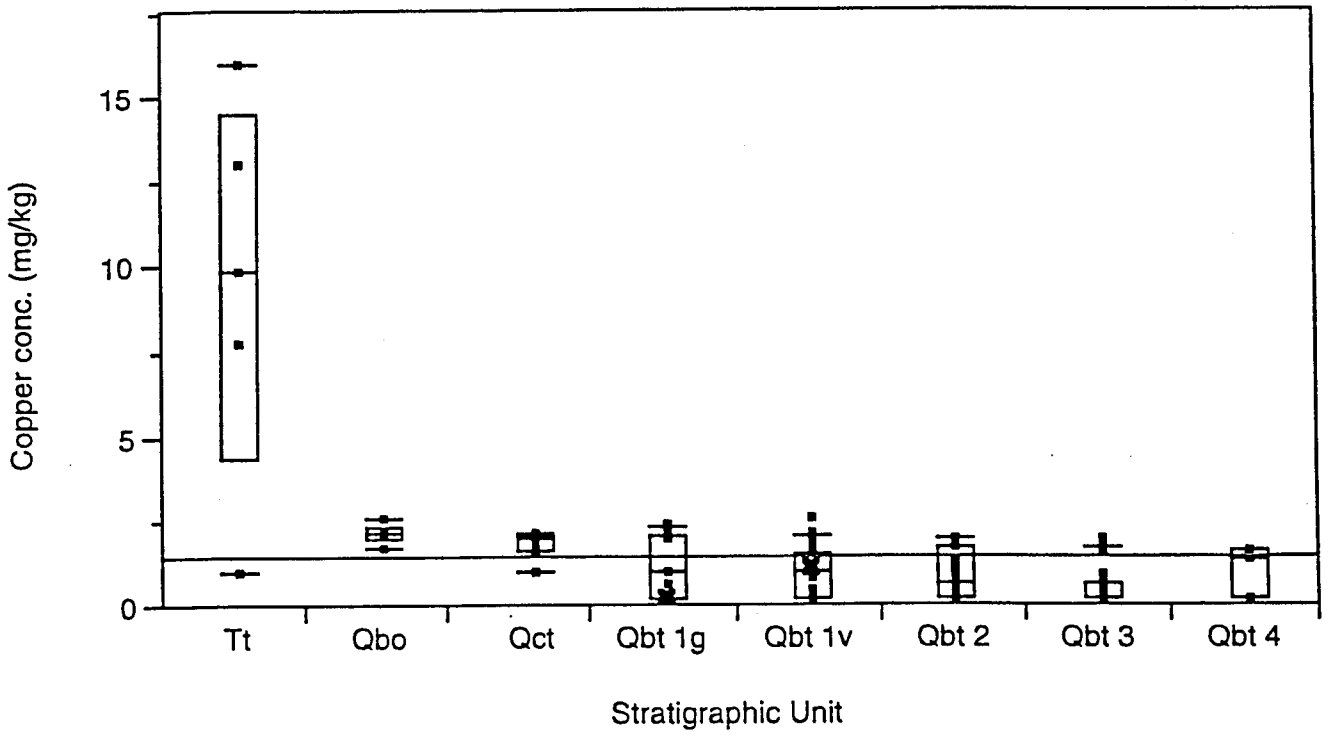
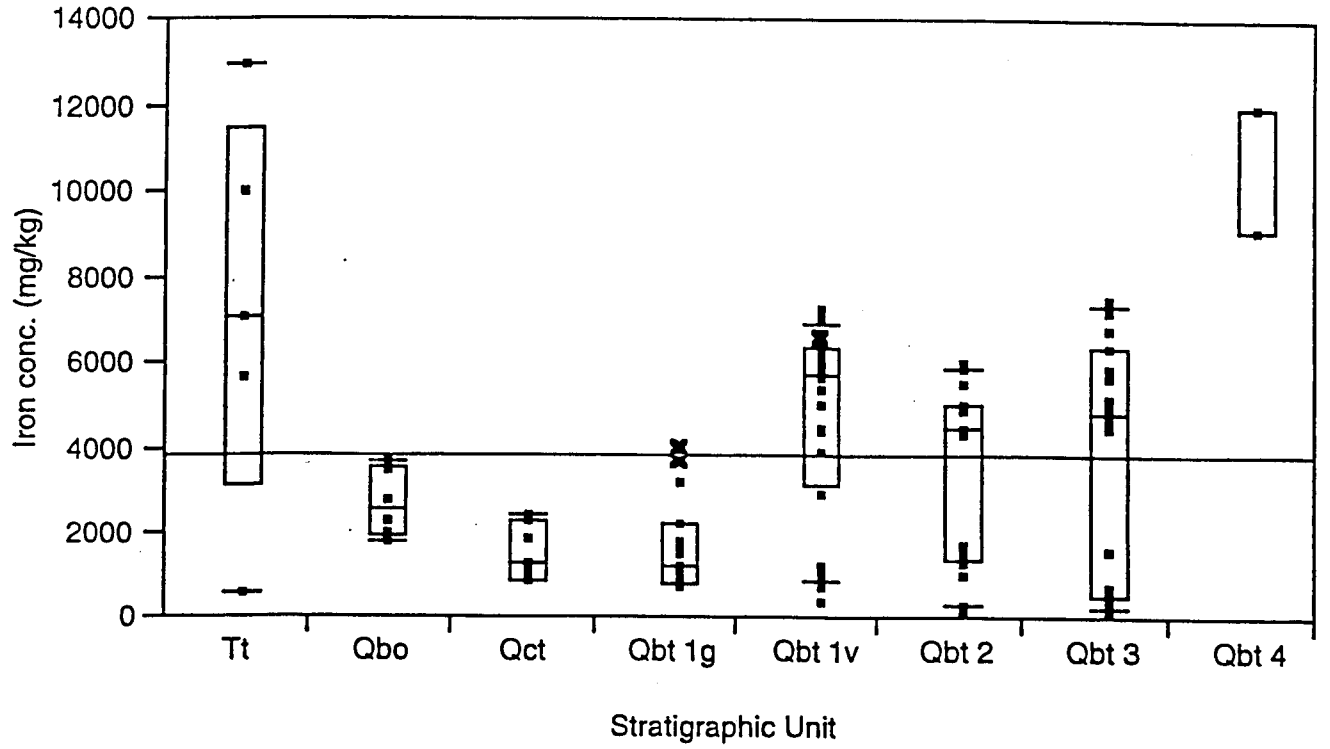


Fig. 4 (Continued)



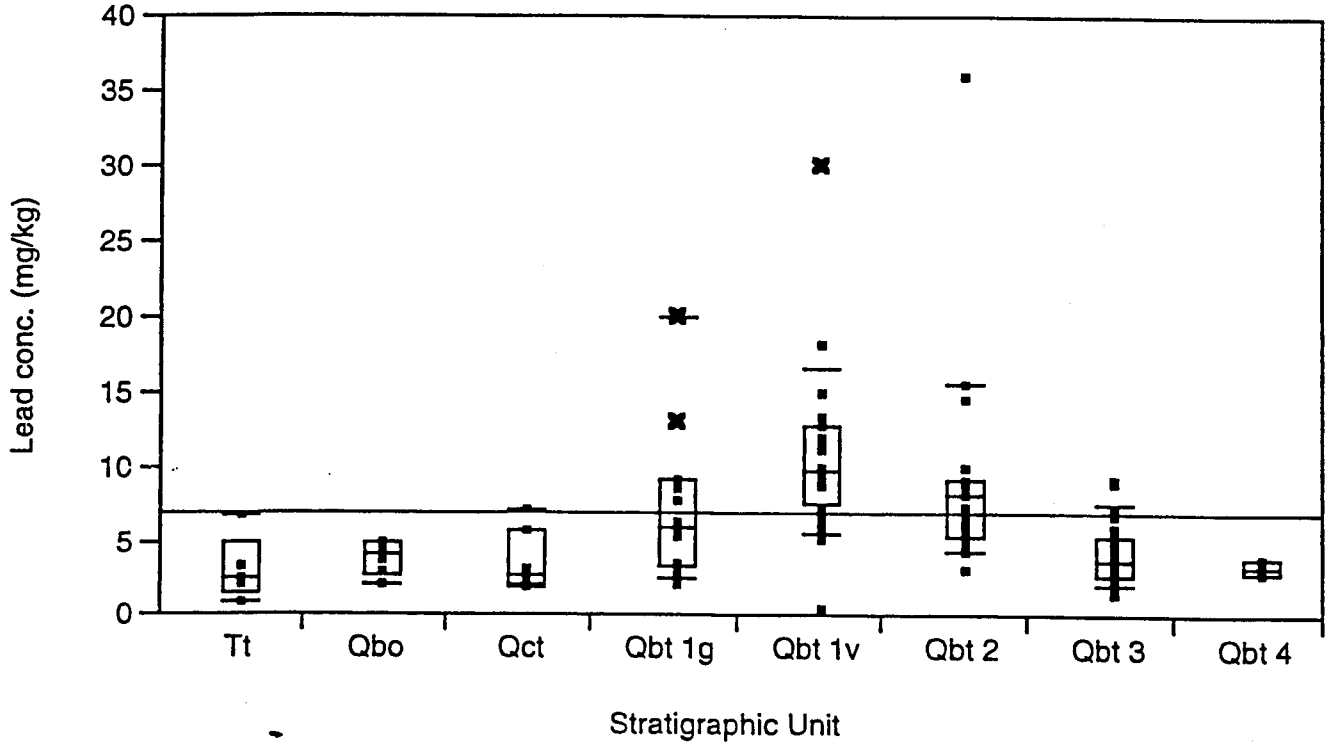
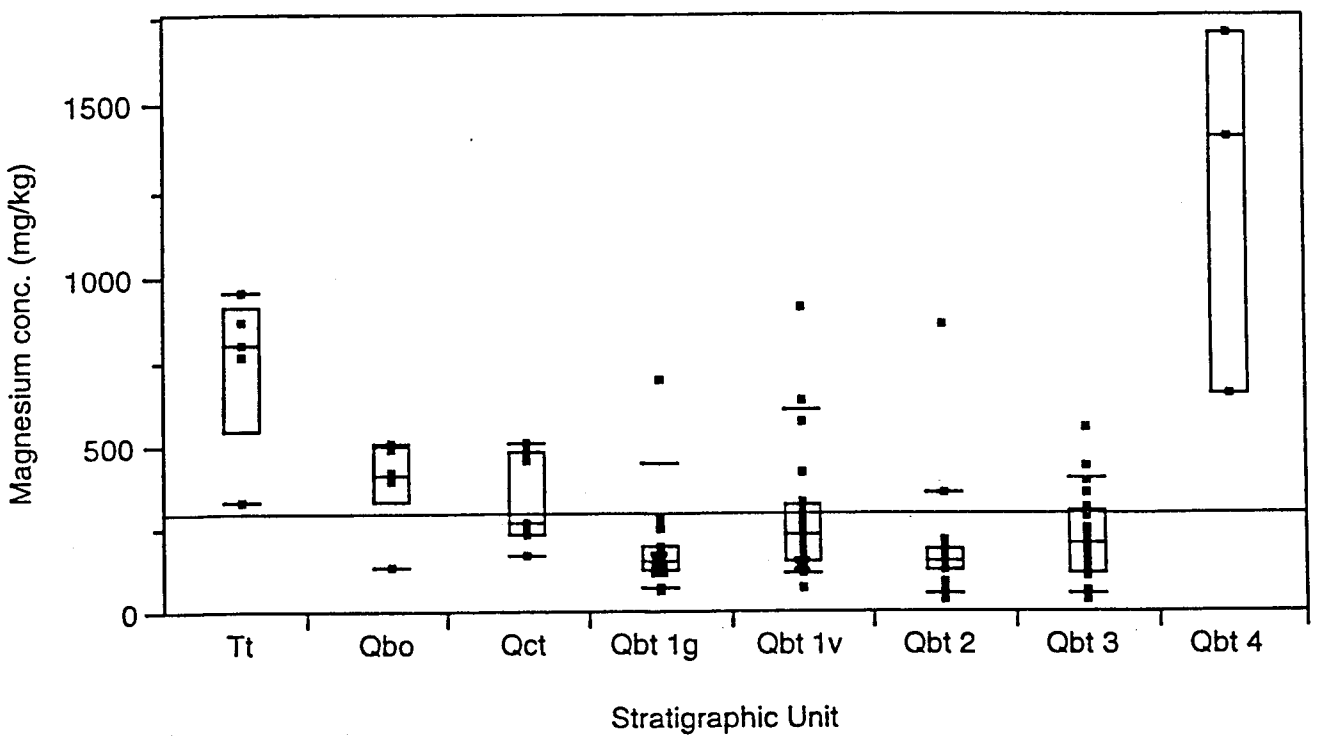
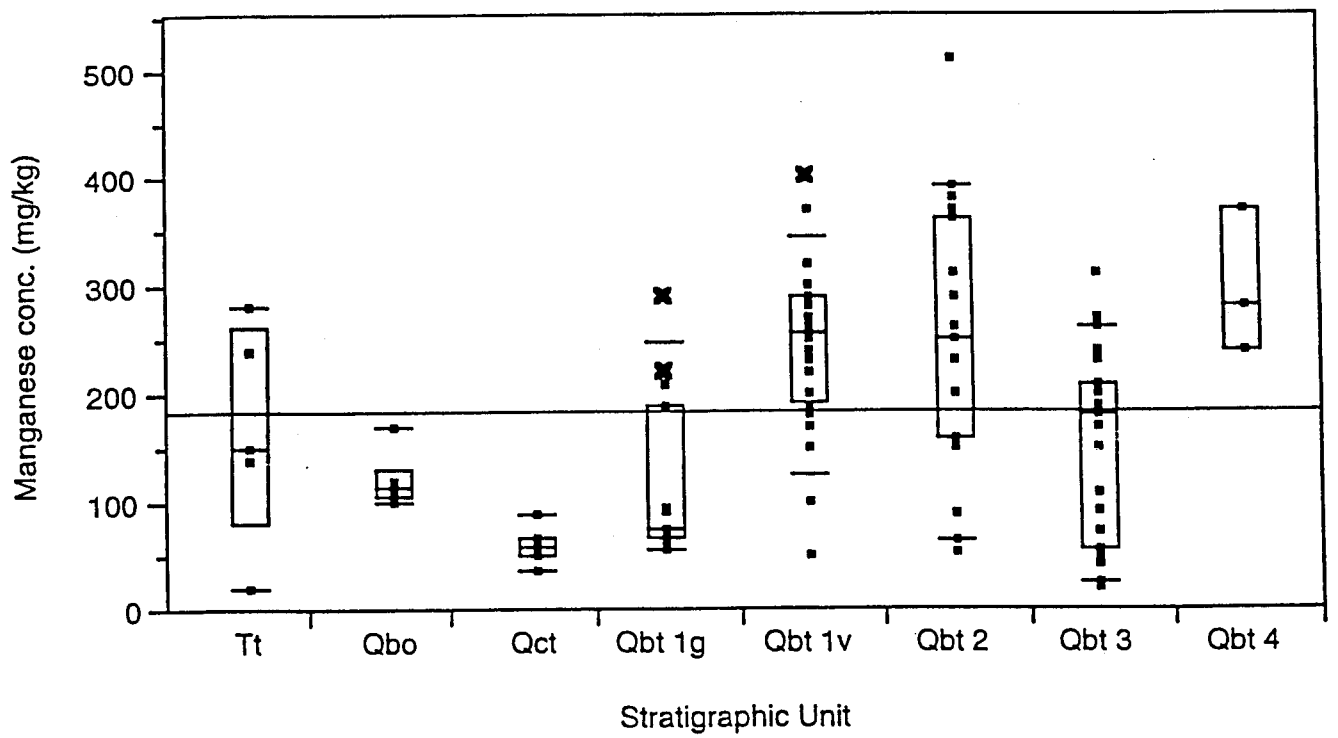


Fig. 4 (Continued)





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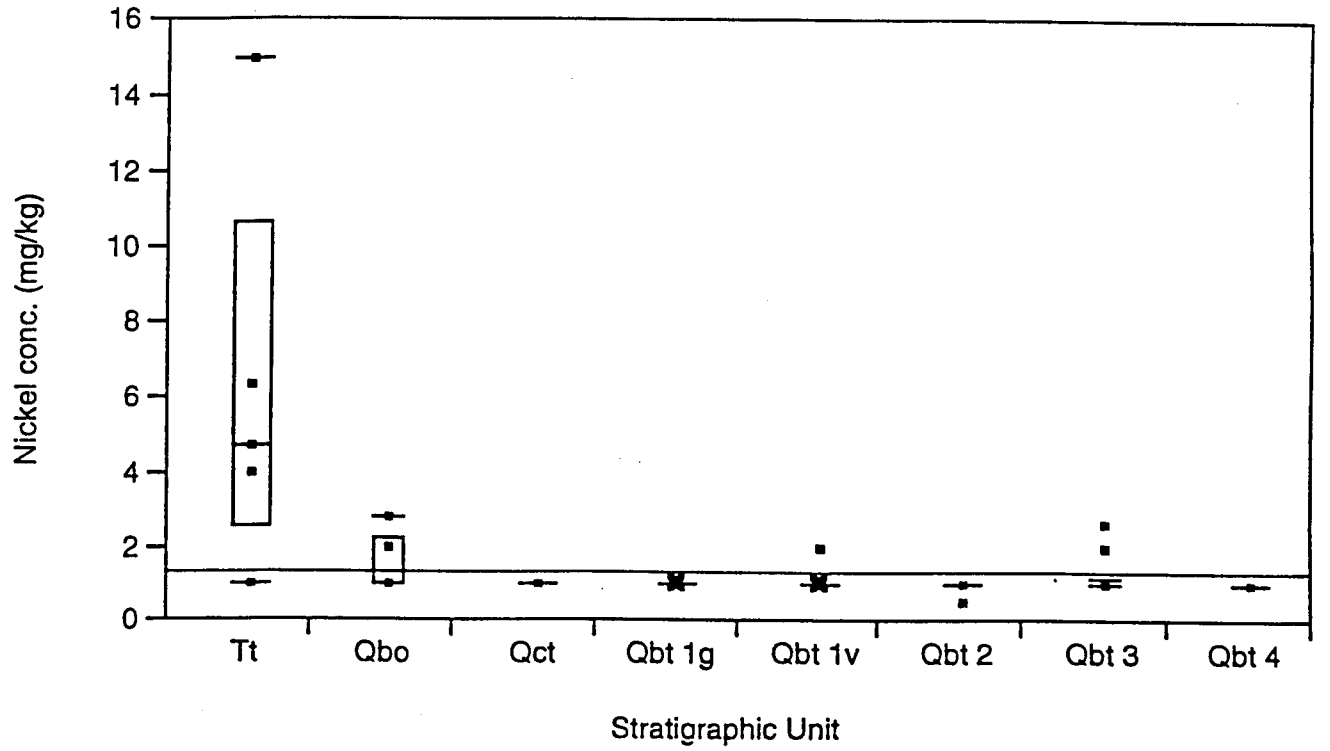

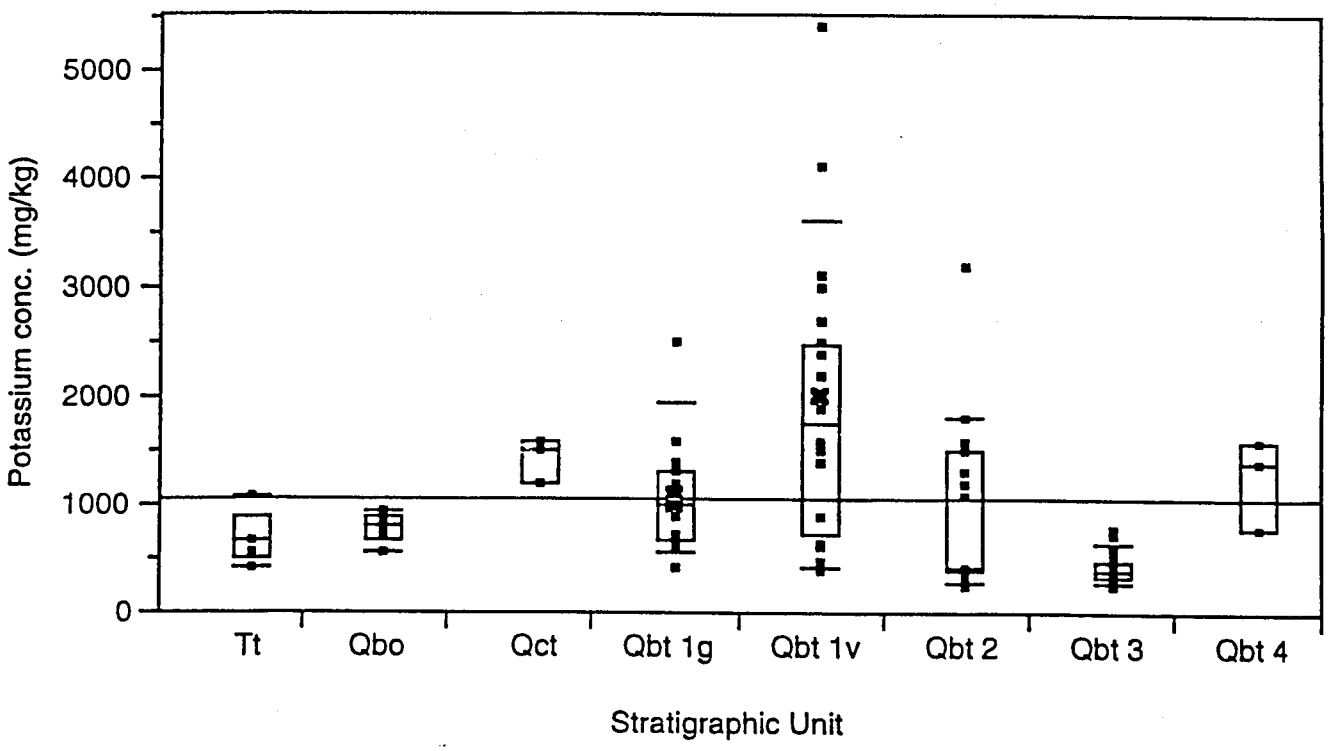

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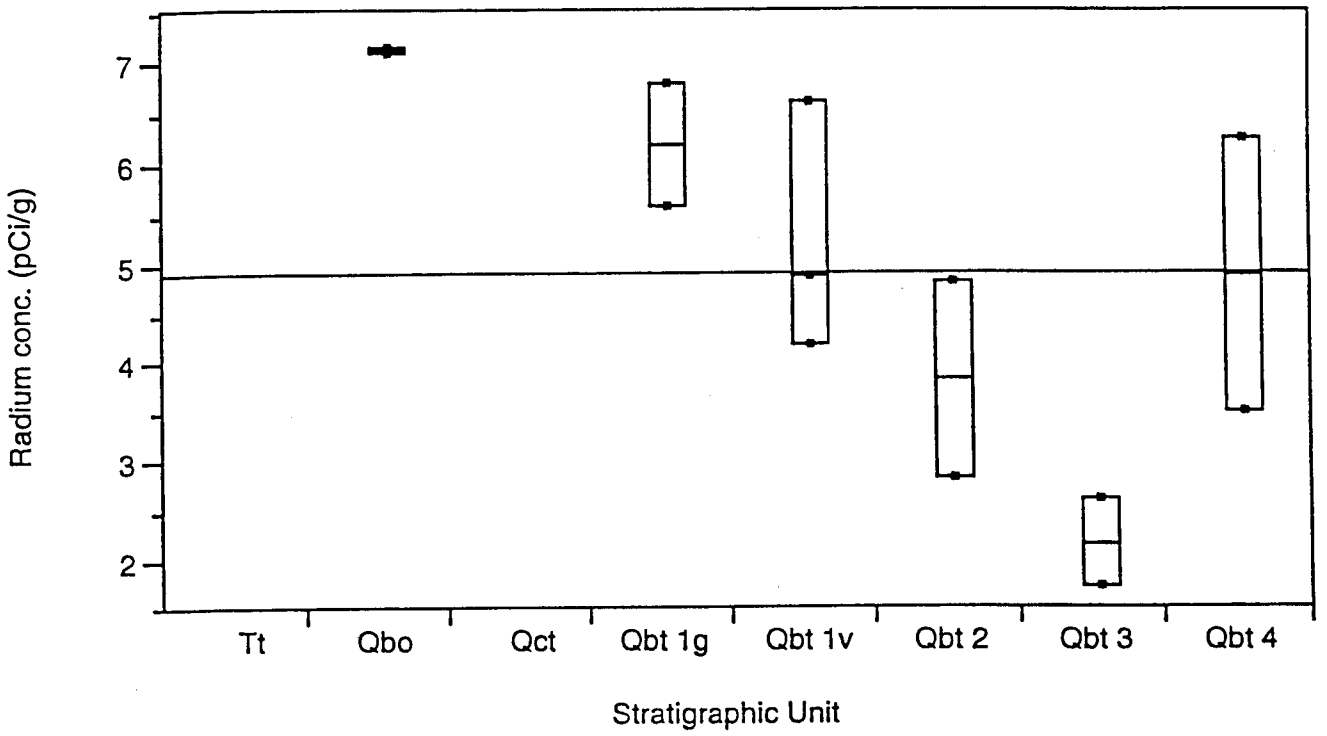

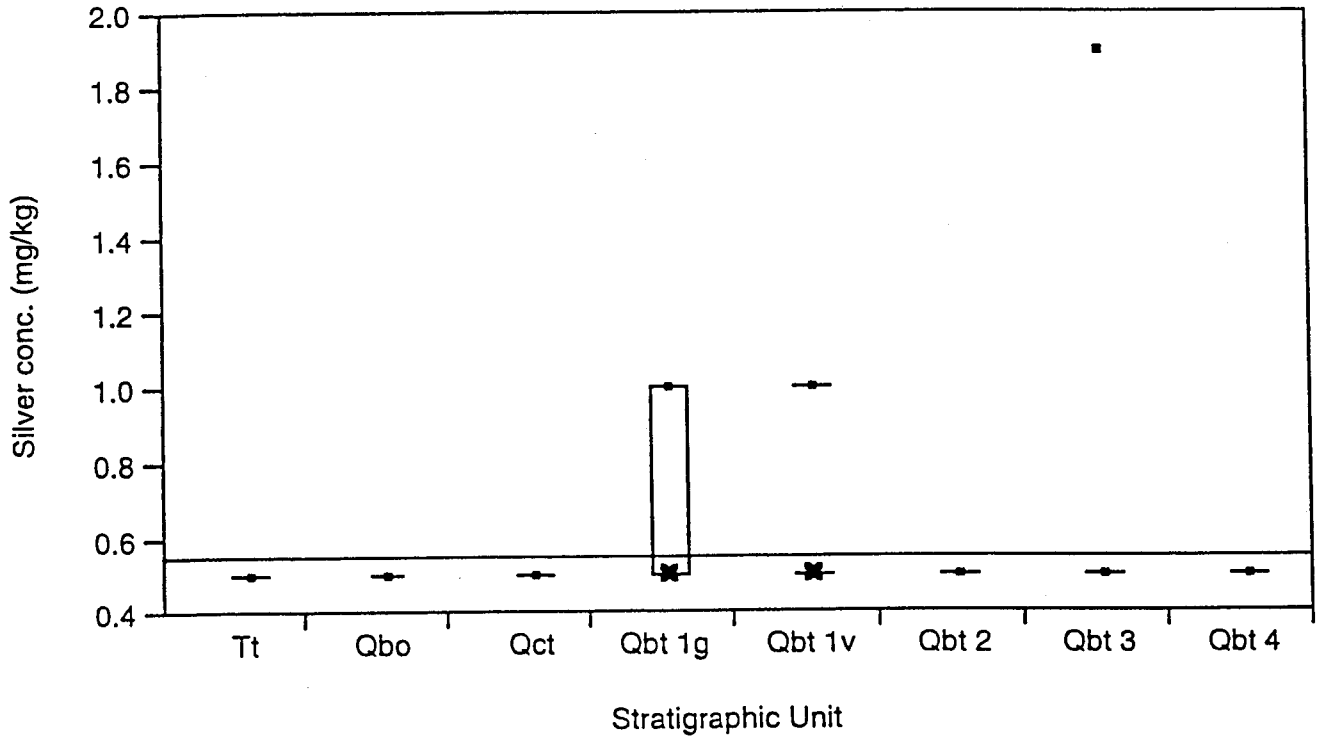

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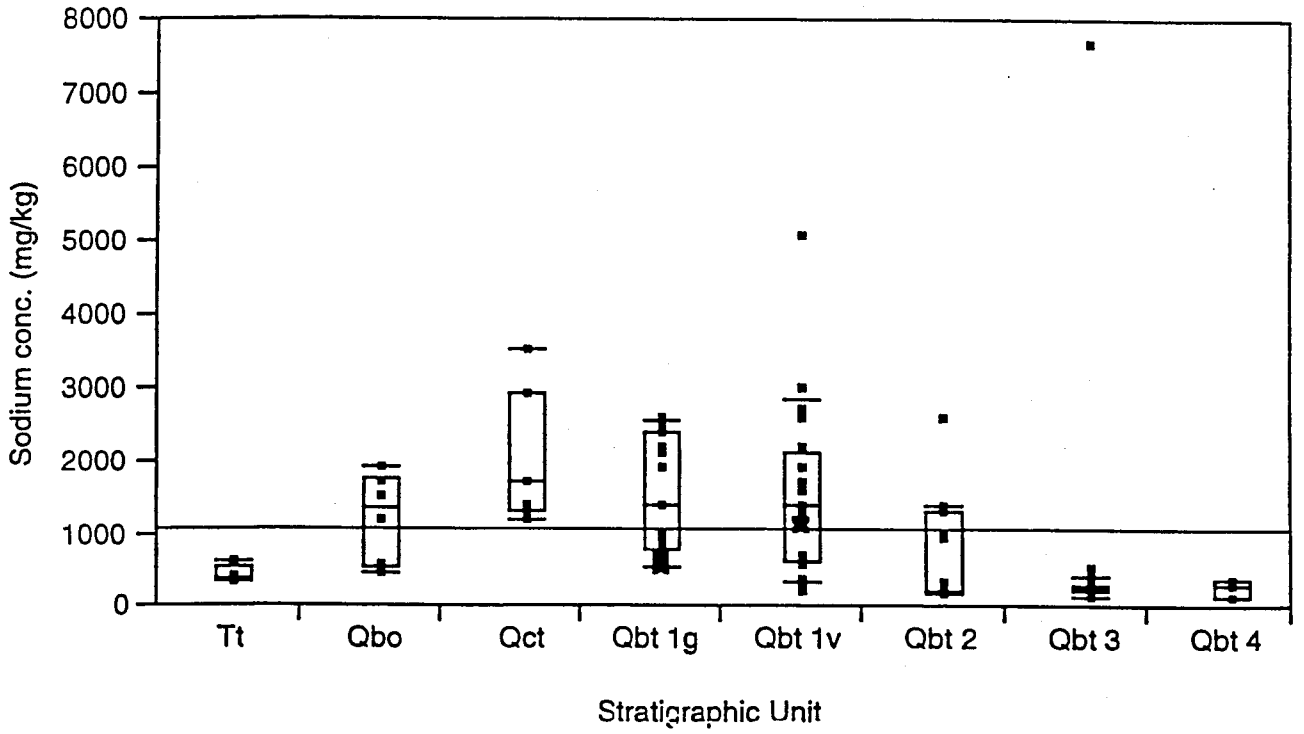

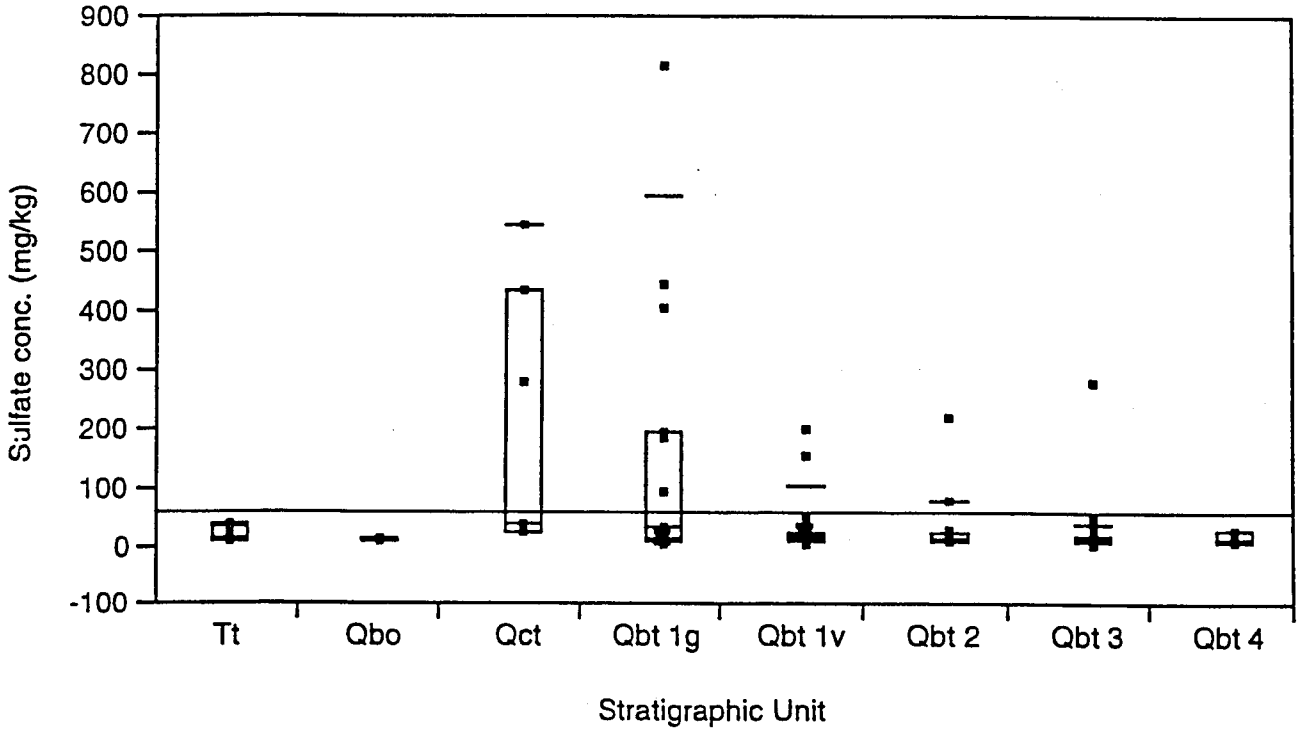

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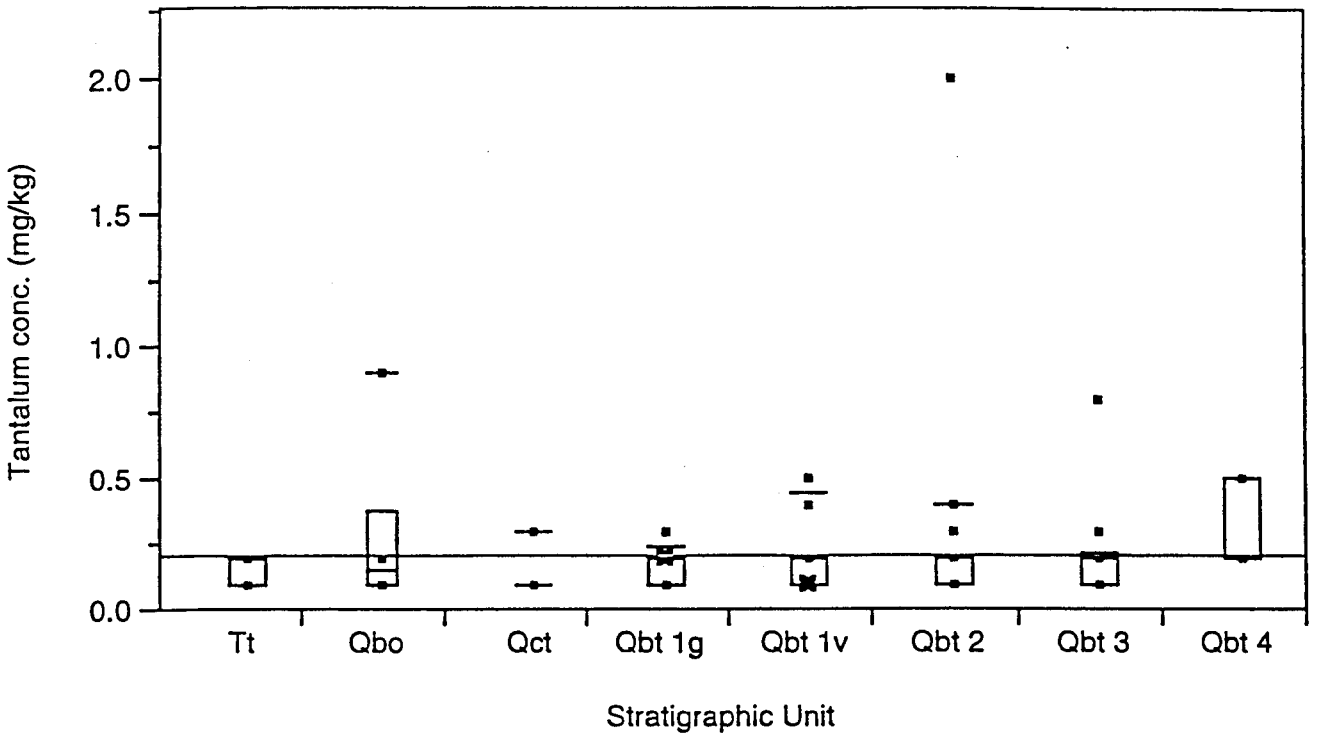


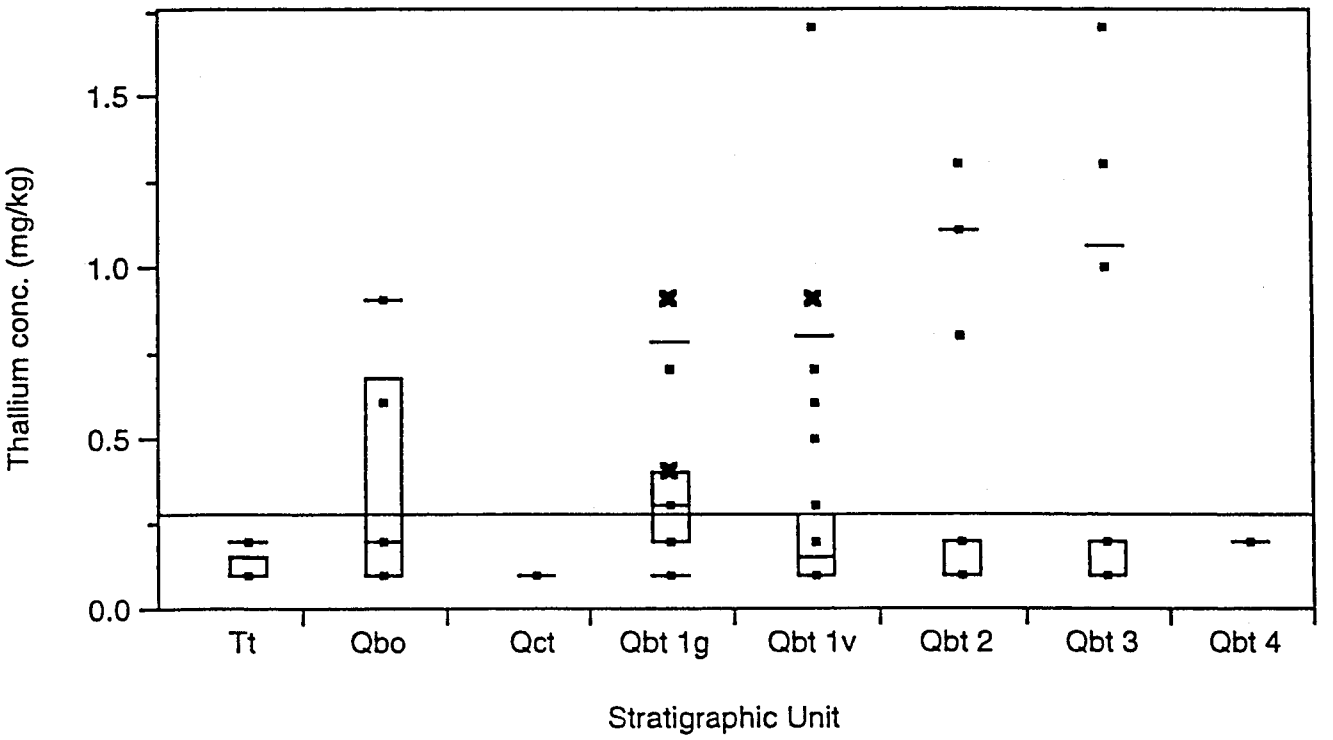
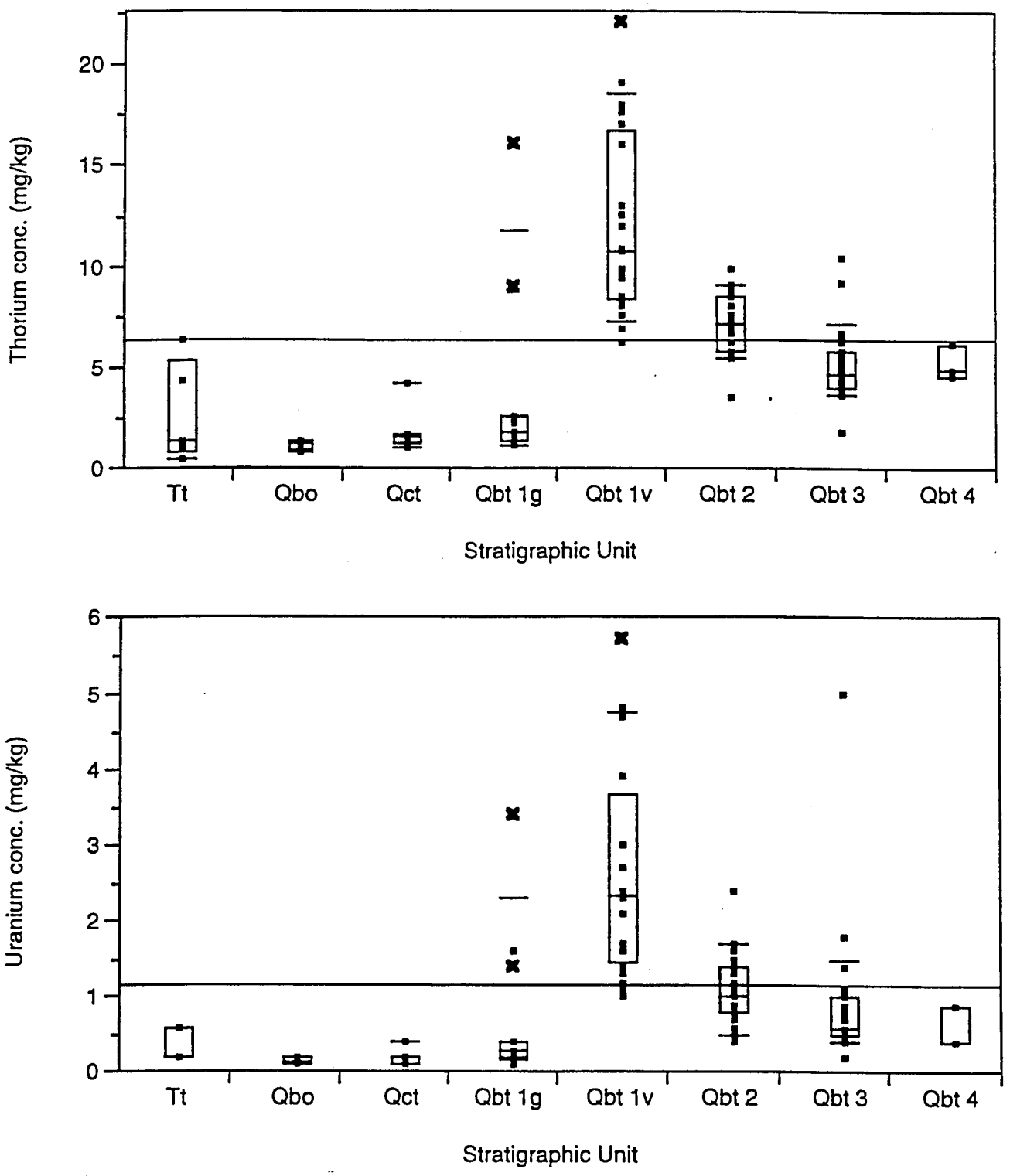


Fig. 4 (Continued)



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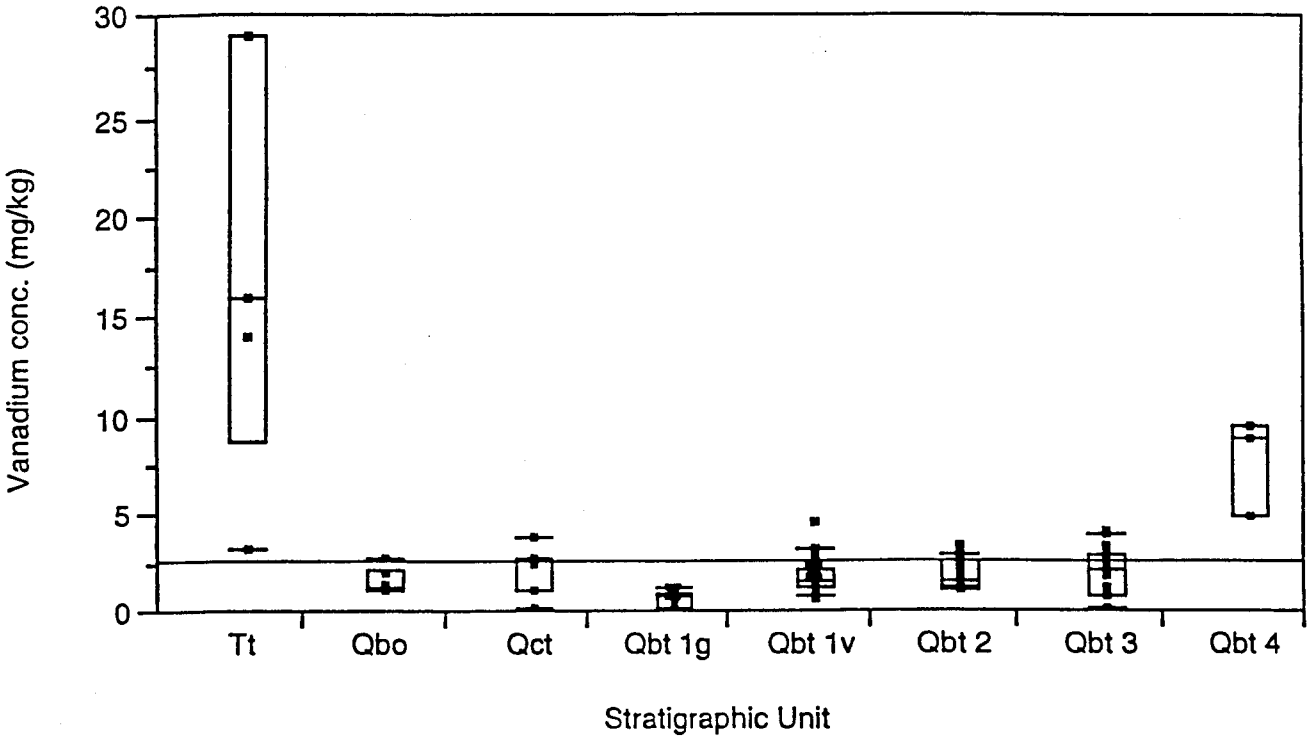


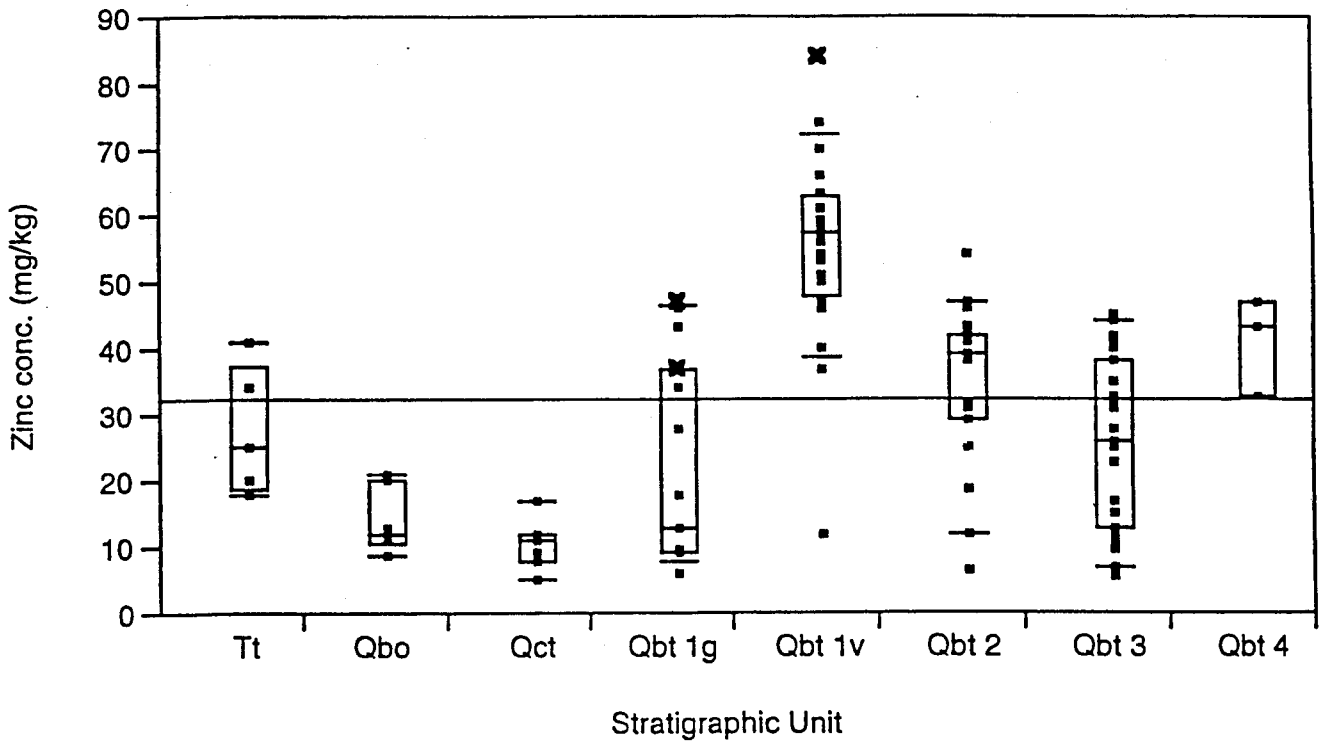


Fig. 4 (Continued)

TABLE II.

SUMMARY OF POPULATION STATISTICS FOR LEACHABLE INORGANIC ANALYTES IN BACKGROUND ROCK SAMPLES.

	Non-detects			Detects			
Analyte	Count	Min	Max	Count	Min	Max	Average
Aluminum	0			106	350	14000	2187
Antimony	97	0.2	0.3	9	0.2	0.4	0.256
Arsenic	52	0.5	0.5	53	0.5	5	1.08
Barium	0			106	1.4	190	18.5
Beryllium	13	0.08	0.14	93	0.15	3.4	0.700
Calcium	0			106	200	4800	825
Chloride	0			106	3.65	802	59.9
Chromium	38	0.5	2	68	0.57	10	1.70
Cobalt	1	1	1	105	0.89	88	23.1
Copper	49	0.5	2	57	0.6	16	2.38
Iron	0			106	190	13000	3867
Lead	0			106	0.6	36	6.95
Magnesium	0			106	39	1700	296
Manganese	0			106	21	510	184
Nickel	97	1	2	9	2	15	4.60
Potassium	0			106	250	5400	1055
Potassium-Total	0			47	28760	47920	38137
Radium-226 (b)	0			13	1.72	7.15	4.92
Silver	105	1	2	1	1.9	1.9	1.9
Sodium	0			106	130	7700	1059
Sulfate	0			106	1.5	815	56.9
Tantalum	85	0.2	0.3	21	0.2	2	0.429
Thallium	82	0.2	0.3	24	0.2	1.7	0.729
Thorium	0			106	0.5	22	6.31
Thorium-Total	0			47	12.7	37.1	22.7
Uranium	14	0.2	0.3	92	0.2	5.7	1.28
Uranium-Total	0			47	2.83	10.1	5.89
Vanadium	16	0.4	1.4	90	0.8	29	3.08
Zinc	0			106	5.3	84	32.1

(a) Includes the three samples from the vapor phase notch.
(b) Radium-226 concentration is a total concentration.
All analyses reported as mg/kg except for radium-226, which is reported as pCi/g.

TABLE III.

Summary of population statistics for leachable elemental concentrations in background samples by stratigraphic unit

	Qct		Qbt 1g		Qbt 1v		Qbt 2		Qbt 3		Qbt 4		Qbo		Tt	
Analyte (1)	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max
Aluminum	1100	3400	490	2500	490	7900	350	4600	400	3000	2100	6200	900	1800	1500	4500
Antimony	<0.2	0.2	<0.2	<0.3	<0.2	0.3	<0.2	0.3	<0.2	0.4	<0.3	<0.3	<0.2	<0.3	<0.2	<0.3
Arsenic	<0.5	0.5	<0.5	0.7	<0.5	2	<0.5	2	<0.5	5	0.6	2	<0.5	<0.5	<0.5	<0.5
Barium	6.7	18	3.6	17	2.4	25	1.4	32	1.7	26	28	42	8.4	23	25	69
Beryllium	0.19	0.95	<0.14	1.4	<0.14	1.5	<0.08	1.1	<0.14	0.91	0.56	1.8	0.32	1.2	<0.14	0.21
Calcium	490	1500	210	4800	200	2800	210	1100	200	2100	730	1800	250	890	990	2700
Chloride	10.1	379	3.65	384	8.2	802	13.5	212	11	279	10.8	14.9	6.7	7.7	9.7	67
Chromium	<0.9	1.8	<0.5	0.94	<0.5	1.7	<0.7	1.6	<0.5	2.1	2.9	5.4	0.73	2.3	<1	10
Cobalt	4.5	40	7.2	23	0.89	88	<1	78	8.6	34	12	25	6.3	10	5.7	11
Copper	<2	2.2	<0.5	2.4	<0.5	2.6	<0.5	2	<0.5	2	<0.5	1.6	1.7	2.6	0.97	16
Iron	880	2400	730	3200	360	7300	200	6000	190	7500	9100	12000	1800	3700	570	13000
Lead	2	7.1	2.2	20	0.6	18.3	3.2	36	1.6	9.1	2.9	4	2.1	5	1	6.7
Magnesium	170	510	69	690	78	910	39	860	42	550	650	1700	140	510	330	950
Manganese	38	90	57	210	52	370	54	510	22	310	240	370	100	170	21	280
Nickel	<2	<2	<2	<2	<2	2	<1	<2	<2	2.6	<2	<2	<2	2.8	<2	15
Potassium	1200	1600	440	2500	390	5400	250	3200	250	800	800	1600	560	960	430	1100
Radium (2)	ND	ND	ND	6.78	ND	6.61	ND	4.82	ND	2.6	ND	6.23	ND	7.15	ND	ND
Silver	<1	<1	<1	<2	<1	<2	<1	<1	<1	1.9	<1	<1	<1	<1	<1	<1
Sodium	1200	3500	530	2600	210	5100	170	2600	150	7700	130	390	450	1900	350	610
Sulfate	22.4	548	1.64	815	1.5	199	9.9	217	3.8	277	10.2	26.4	8.5	12.7	10.5	38.6
Tantalum	<0.2	0.3	<0.2	0.3	<0.2	0.5	<0.2	2	<0.2	0.8	<0.3	0.5	<0.3	0.9	<0.2	0.2
Thallium	<0.2	<0.2	<0.2	0.7	<0.2	1.7	<0.2	1.3	<0.2	1.7	<0.3	<0.3	<0.2	0.9	<0.2	<0.3
Thorium	1.1	4.2	1.2	8.8	6.2	19.1	3.5	9.9	1.9	10.4	4.6	6.1	0.9	1.4	0.5	6.4
Uranium	<0.2	0.4	<0.2	1.6	1	4.8	0.4	2.4	0.2	5	0.4	0.9	<0.2	0.2	<0.3	0.6
Vanadium	<0.5	3.8	<0.4	1.3	<1.4	4.6	1.2	3.4	<0.5	4.2	5	9.5	1.1	2.8	3.3	29
Zinc	5.3	17	6.1	46	12	74	6.7	54	5.5	45	33	47	8.9	21	18	41

Sample sizes are: Qct, n=7; Qbt 1g, n=13; Qbt 1v, n=23; Qbt 2, n=19; Qbt 3, n=27; Qbt 4, n=3; Qbo, n=6, except arsenic n=5; Tt, n=5.

(1) - All values are in mg/kg unless otherwise noted.
(2) - Units are pCi/g.

ND - Not determined.

TABLE IV.

Summary of Mann-Whitney significance levels for comparisons between units of the Tshirege Member

Analyte	Qbt1g vs Qbt1v	Qbt1g vs Qbt2	Qbt1v vs Qbt2	Qbt1g vs Qbt3	Qbt1v vs Qbt3	Qbt 1 vs Qbt 2	Qbt 1 vs Qbt 3	Qbt 2 vs Qbt 3	Data groups			
Aluminum	0.00	0.09	0.04	0.79	0.00	0.49	0.00	0.01	Qbt 1g23	Qbt 1v		
Barium	0.28	0.00	0.02	0.09	0.39	0.00	0.16	0.05	Qbt 123			
Beryllium	0.22	0.45	0.18	0.87	0.01	0.55	0.09	0.09	Qbt 123			
Calcium	0.11	0.38	0.00	0.63	0.00	0.00	0.04	0.70	Qbt 1	Qbt 23		
Chloride	0.88	0.26	0.03	0.02	0.00	0.05	0.00	0.00	Qbt 1	Qbt 2	Qbt 3	
Cobalt	0.00	0.04	0.06	0.21	0.00	0.69	0.10	0.09	Qbt 1g3	Qbt 1v2		
Iron	0.00	0.00	0.06	0.14	0.34	0.94	0.99	0.49	Qbt 1g	Qbt 1v23		
Lead	0.00	0.07	0.06	0.08	0.00	0.63	0.00	0.00	Qbt 123			
Magnesium	0.04	0.73	0.00	0.40	0.26	0.04	0.69	0.19	Qbt 1g2	Qbt 1v3		
Manganese	0.00	0.00	0.67	0.03	0.00	0.06	0.27	0.02	Qbt 1g	Qbt 1v2	Qbt 3	
Potassium	0.07	0.14	0.00	0.00	0.00	0.00	0.00	0.08	Qbt 1g2	Qbt 1v	Qbt 3	
Sodium	0.48	0.00	0.00	0.00	0.00	0.00	0.00	0.74	Qbt 1	Qbt 23		
Sulfate	0.09	0.10	0.68	0.00	0.00	0.30	0.00	0.07	Qbt 123			
Thorium	0.00	0.00	0.00	0.00	0.00	0.33	0.07	0.00	Qbt 1g	Qbt 1v	Qbt 2	Qbt 3
Uranium	0.00	0.00	0.00	0.00	0.00	0.30	0.13	0.03	Qbt 1g	Qbt 1v	Qbt 2	Qbt 3
Vanadium	0.00	0.00	0.80	0.00	0.79	0.02	0.13	0.95	Qbt 1g	Qbt 1v23		
Zinc	0.00	0.00	0.00	0.11	0.00	0.09	0.00	0.08	Qbt 1g23	Qbt 1v		

TABLE V.

STATISTICAL DISTRIBUTION OF THE BANDELIER TUFF BACKGROUND DATA SET INORGANIC ANALYTES. THESE DATA ARE FOR THE NITRIC ACID DISSOLUTION EXTRACTION METHOD (EPA METHOD 3050)

Analyte	Statistical Distribution
Aluminum	Square root transformed data are approximately normally distributed.
Antimony	Only 9 of 106 total values are detects, no distribution was estimated.
Arsenic	Only 53 of 105 total values are detects, no distribution was estimated.
Barium	Data are approximately normally distributed.
Beryllium	Square root transformed data are approximately normally distributed.
Calcium	Log transformed data are approximately normally distributed.
Chloride	Log transformed data are approximately normally distributed.
Chromium	Only 68 of 106 total values are detects, no distribution was estimated.
Cobalt	Square root transformed data are approximately normally distributed.
Copper	Only 57 of 106 total values are detects, no distribution was estimated.
Iron	Each data subgroup was bimodally distributed, instead of estimating a mixture distribution, we will use the maximum value per subgroup as a background screening value.
Lead	Square root transformed data are approximately normally distributed, which include a statistical outlier that was not deleted from the combined data group (36 mg/kg).
Magnesium	Square root transformed data are approximately normally distributed.
Manganese	Data are approximately normally distributed.
Nickel	Only 9 of 106 total values are detects, no distribution was estimated.
Potassium	Square root transformed data are approximately normally distributed.
Potassium-Total	Data are approximately normally distributed.
Radium	Only 13 of 106 total values are detects, no distribution was estimated.
Silver	Only 1 of 106 total values is a detect, no distribution was estimated.
Sodium	For data group Qbt 1, square root transformed data are approximately normally distributed. For data group Qbt 23, log transformed data are approximately normally distributed.
Sulfate	Each data subgroup was bimodally distributed, instead of estimating a mixture distribution, we will use the maximum value per subgroup as a background screening value.
Tantalum	Only 21 of 106 total values are detects, no distribution was estimated.
Thallium	Only 24 of 106 total values are detects, no distribution was estimated.
Thorium	Square root transformed data are approximately normally distributed.
Thorium-Total	Statistical distribution was not evaluated due to a small sample size per stratigraphic unit.
Uranium	Square root transformed data are approximately normally distributed.
Uranium-Total	Statistical distribution was not evaluated due to a small sample size per stratigraphic unit.
Vanadium	Data are approximately normally distributed.
Zinc	Data within each subgroup are approximately normally distributed.

TABLE VI.

SUMMARY OF CALCULATED RAW UTLs AND MAXIMUM CONCENTRATIONS FOR BANDELIER TUFF UNITS QBT 123 GROUPS AND SUBGROUPS

Aluminum

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	UTL_{95th} (sqrt)
Qbt 1g23	59	350	1300	4600	1467	959	0.0001	3698
Qbt 1v	23	490	2700	7900	2945	1716		8173
All Qbt 123 data	82	350	1700	7900	1882	1380		5066

Antimony

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	Max. detect
Qbt 1g	13	0.1	0.2	0.2	0.169	0.048	0.0568	ND
Qbt 1v	23	0.1	0.1	0.3	0.135	0.057		0.3
Qbt 2	19	0.1	0.2	0.3	0.168	0.058		0.3
Qbt 3	27	0.1	0.2	0.4	0.178	0.070		0.4
All Qbt 123 data	82	0.1	0.2	0.4	0.162	0.062		0.4

Arsenic

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	Max. detect
Qbt 1g	13	0.3	0.3	0.7	0.362	0.126	0.0013	0.7
Qbt 1v	23	0.3	0.6	2	0.626	0.398		2
Qbt 2	19	0.3	0.3	2	0.547	0.441		2
Qbt 3	27	0.3	0.8	5	1.085	1.112		5
All Qbt 123 data	82	0.3	0.5	5	0.717	0.748		5

Barium

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	UTL_{95th}
All Qbt 123 data	82	1.4	14	32	13.4	7.17	NA	28.0

Beryllium

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	UTL_{95th} (sqrt)
All Qbt 123 data	82	0.04	0.57	1.5	0.570	0.371	NA	1.53

Calcium

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	UTL_{95th} by sim
Qbt 1	36	200	885	4800	1073	926	0.0017	4139
Qbt 23	46	200	400	2100	560	416		1524
All Qbt 123 data	82	200	520	4800	785	729		2431

TABLE VI (CONTINUED).

SUMMARY OF CALCULATED RAW UTLs AND MAXIMUM CONCENTRATIONS FOR BANDELIER TUFF UNITS QBT 123 GROUPS AND SUBGROUPS

Chloride

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	UTL_{95th} by sim
Qbt 1	36	3.65	42.5	802	118.0	194.7	0	404.9
Qbt 2	19	13.5	18	212	33.0	44.7		107.2
Qbt 3	27	11	13.1	279	25.2	51.0		64.8
All Qbt 123 data	82	3.65	19.65	802	67.8	140.2		237.0

Chromium

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	Max. detect
Qbt 1g	13	0.25	0.6	0.94	0.556	0.230	0.0391	0.94
Qbt 1v	23	0.25	0.6	1.7	0.733	0.451		1.7
Qbt 2	19	0.35	0.76	1.6	0.913	0.461		1.6
Qbt 3	27	0.25	0.9	2.1	1.051	0.596		2.1
All Qbt 123 data	82	0.25	0.705	2.1	0.851	0.507		2.1

Cobalt

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	UTL_{95th}
Qbt 1g3	40	7.2	14	34	14.9	5.53	0.0002	27.4
Qbt 1v2	42	0.5	31.5	88	35.5	25.5		106.7
All Qbt 123 data	82	0.5	15.5	88	25.5	21.2		72.5

Copper

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	Max. detect
Qbt 1g	13	0.25	2	2.4	1.488	0.810	0.0011	2.4
Qbt 1v	23	0.25	1	2.6	1.020	0.724		2.6
Qbt 2	19	0.25	0.65	2	0.887	0.689		2
Qbt 3	27	0.25	0.25	2	0.582	0.605		2
All Qbt 123 data	82	0.25	0.65	2.6	0.919	0.745		2.6

Iron

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	UTL_{95th}
Qbt 1v23	69	190	4900	7500	4075	2453	0.0039	9035
Qbt 1g	13	730	1200	3200	1390	698		3254
All Qbt 123 data	82	190	4500	7500	3650	2469		8642

Lead

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	UTL_{95th} (sqrt)
Qbt 1g23	59	1.6	5.3	36	6.33	5.23	0	16.2
Qbt 1v	23	0.6	9.6	18.3	9.85	3.69		21.9
All Qbt 123 data	82	0.6	6.35	36	7.32	5.08	NA	18.1

TABLE VI (CONTINUED).

SUMMARY OF CALCULATED RAW UTLS AND MAXIMUM CONCENTRATIONS FOR BANDELIER TUFF UNITS QBT 123 GROUPS AND SUBGROUPS

Magnesium

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	UTL_{95th} (sqrt)
Qbt 1g2	32	39	150	860	195	167	0.0245	548
Qbt 1v3	50	42	230	910	252	164		628
All Qbt 123 data	82	39	190	910	229	166		582

Manganese

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	UTL_{95th}
Qbt 1v2	42	52	250	510	245.5	98.2	0	533
Qbt 1g	13	57	72	210	93.4	49.2		273
Qbt 3	27	22	180	310	155.0	87.0		426
All Qbt 123 data	82	22	200	510	191.6	105.7		488

Nickel

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	Max. detect
Qbt 1g	13	1	1	1	1	0	0.262	ND
Qbt 1v	23	1	1	2	1.043	0.209		2
Qbt 2	19	0.5	1	1	0.974	0.115		ND
Qbt 3	27	1	1	2.6	1.096	0.357		2.6
All Qbt 123 data	82	0.5	1	2.6	1.038	0.241		2.6

Potassium

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	UTL_{95th} (sqrt)
Qbt 1g2	32	250	720	3200	977	688	0	2725
Qbt 1v	23	390	1600	5400	1872	1256		5541
Qbt 3	27	250	390	800	420	132		735
All Qbt 123 data	82	250	615	5400	1045	970		3099

Potassium-Total

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	UTL_{95th}
All Qbt 123 data	47	28760	38090	47920	38137	3347	NA	45102

Radium (pCi/g)

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	Max. detect
Qbt 1g	2	5.58	6.18	6.78	6.180	0.849	0.0965	6.78
Qbt 1v	3	4.18	4.89	6.61	5.227	1.249		6.61
Qbt 2	2	2.81	3.815	4.82	3.815	1.421		4.82
Qbt 3	2	1.72	2.16	2.6	2.160	0.622		2.60
All Qbt 123 data	9	1.72	4.82	6.78	4.443	1.780		6.78

TABLE VI (CONTINUED).

SUMMARY OF CALCULATED RAW UTLS AND MAXIMUM CONCENTRATIONS FOR BANDELIER TUFF UNITS QBT 123 GROUPS AND SUBGROUPS

Silver

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	Max. detect
Qbt 1g	13	0.5	0.5	1	0.692	0.253	0.0041	ND
Qbt 1v	23	0.5	0.5	1	0.565	0.172		ND
Qbt 2	19	0.5	0.5	0.5	0.5	0		ND
Qbt 3	27	0.5	0.5	1.9	0.552	0.269		1.9
All Qbt 123 data	82	0.5	0.5	1.9	0.566	0.211		1.9

Sodium

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	UTL_{95th}
Qbt 1 (sqrt)	36	210	1500	5100	1613	998	0	4289
Qbt 23 (by sim)	46	150	255	7700	607	1174		1941
All Qbt 123 data (by sim)	82	150	470	7700	1048	1204		4604

Sulfate

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	Max. detect
All Qbt 123 data	82	1.5	14.55	815	53.3	118	NA	815

Tantalum

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	Max. detect
Qbt 1g	13	0.1	0.2	0.3	0.177	0.060	0.975	0.3
Qbt 1v	23	0.1	0.2	0.5	0.200	0.117		0.5
Qbt 2	19	0.1	0.2	2	0.274	0.425		2
Qbt 3	27	0.1	0.2	0.8	0.189	0.134		0.8
All Qbt 123 data	82	0.1	0.2	2	0.210	0.227		2

Thallium

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	Max. detect
Qbt 1g	13	0.1	0.3	0.7	0.277	0.154	0.1385	0.7
Qbt 1v	23	0.1	0.1	1.7	0.270	0.355		1.7
Qbt 2	19	0.1	0.2	1.3	0.300	0.354		1.3
Qbt 3	27	0.1	0.2	1.7	0.289	0.392		1.7
All Qbt 123 data	82	0.1	0.2	1.7	0.284	0.339		1.7

Thorium

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	UTL_{95th} (sqrt)
Qbt 1g	13	1.2	1.7	8.8	2.33	2.01	0	7.69
Qbt 1v	23	6.2	10.7	19.1	11.68	4.00		22.14
Qbt 2	19	3.5	7.1	9.9	7.15	1.56		11.50
Qbt 3	27	1.9	4.7	10.4	5.11	1.72		9.29
All Qbt 123 data	82	1.2	6.35	19.1	6.99	4.16		16.85

TABLE VI (CONTINUED).

SUMMARY OF CALCULATED RAW UTLS AND MAXIMUM CONCENTRATIONS FOR BANDELIER TUFF UNITS QBT 123 GROUPS AND SUBGROUPS

Thorium-Total

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	Max. detect
Qbt1g	9	21.32	29.39	37.06	29.29	4.267	0	37.06
Qbt1v	18	19.14	26.46	30.08	25.73	3.286		30.08
Qbt2	5	16.25	19.67	25.93	20.39	3.503		25.93
Qbt3	6	12.89	15.05	16.32	14.61	1.402		16.32
All Qbt 123 data	47	12.66	22.56	37.06	22.68	6.343		37.06

Uranium

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	UTL_{95th} (sqrt)
Qbt 1g	13	0.1	0.2	1.6	0.362	0.384	0	1.39
Qbt 1v	23	1	2.3	4.8	2.474	1.270		5.93
Qbt 2	19	0.4	1	2.4	1.105	0.484		2.48
Qbt 3	26	0.2	0.55	1.8	0.727	0.356		1.64
All Qbt 123 data	81	0.1	1	4.8	1.253	1.100		3.68

Uranium-Total

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	Max. detect
Qbt1g	9	5.977	7.853	10.13	7.908	1.239	0	10.13
Qbt1v	18	4.713	7.142	7.592	6.869	0.807		7.592
Qbt2	5	4.322	4.728	7.123	5.135	1.146		7.123
Qbt3	6	3.173	3.3345	4.371	3.467	0.454		4.371
All Qbt 123 data	47	2.832	6.737	10.13	5.890	1.980		10.13

Vanadium

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	UTL_{95th}
Qbt 1v23	69	0.25	1.7	4.6	1.929	1.030	0	4.01
Qbt 1g	13	0.2	0.5	1.3	0.662	0.377		1.67
All Qbt 123 data	82	0.2	1.4	4.6	1.728	1.062		3.88

Zinc

Data group	Count	minimum	median	maximum	Mean	Std Dev	Prob>ChiSq (1)	UTL_{95th}
Qbt 1g23	59	5.5	28	54	26.8	14.1	0	55.5
Qbt 1v	23	12	57	74	53.8	13.3		84.6
All Qbt 123 data	82	5.5	37.5	74	34.4	18.4		71.6

(1) Probability that the Qbt 1, Qbt 2, and Qbt 3 data are drawn from the same distribution, or are statistically not different, as measured the Wilcoxon/Kruskal-Wallis test. The Kruskal-Wallis is a three or more data group extension of the Wilcoxon rank sum test. Probabilities less than 0.05 indicate that there is a statistically significant difference between strata, and a probability greater than 0.05 indicates that there is no statistically significant difference between strata.
UTL95th - 95% upper tolerance limit of the 95th percentile calculated using normal theory.
UTL95th (sqrt) - 95% upper tolerance limit of the 95th percentile calculated using normal theory on square root transformed data.
UTL95th by sim - 95% upper tolerance limit of the 95th percentile calculated using log-transformed data and computer simulation.
Max. detect. - maximum detected value is proposed as a background screening value due to a small Count of detects.
NA - Not applicable.
ND - Not detected.

TABLE VII.

BACKGROUND SCREENING VALUES FOR INORGANIC ANALYTES COMPILED BY GEOLOGICAL UNITS

Analyte[1]	Qct	Qbt 1g	Qbt 1v	Qbt 2	Qbt 3	Qbt 4	Qbo	Tt
Aluminum	3400	3700	8170	3700	3700	6200	1800	4500
Antimony	0.2	<0.3	0.3	0.3	0.4	<0.3	<0.3	<0.3
Arsenic	0.5	0.7	2	2	5	2	<0.5	<0.5
Barium	18	28.0	28.0	28.0	28.0	42	23	69
Beryllium	0.95	1.53	1.53	1.53	1.53	1.8	1.2	0.21
Calcium	1500	4140	4140	1520	1520	1800	890	2700
Chloride	379	405	405	107	64.8	14.9	7.7	67
Chromium	1.8	0.94	1.7	1.6	2.1	5.4	2.3	10
Cobalt	40	27.4	107	107	27.4	25	10	11
Copper	2.2	2.4	2.6	2	2	1.6	2.6	16
Iron	2400	3250	9040	9040	9040	12000	3700	13000
Lead	7.1	16.2	21.9	16.2	16.2	4	5	6.7
Magnesium	510	548	628	548	628	1700	510	950
Manganese	90	273	533	533	426	370	170	280
Nickel	<2	<2	2	<2	2.6	<2	2.8	15
Potassium	1600	2730	5540	2730	735	1600	960	1100
Potassium-Total	NA	45100	45100	45100	45100	45300	37200	33800
Radium-226 [2]	NA	6.78	6.61	4.82	2.6	6.23	7.15	NA
Silver	<1	<2	<2	<1	1.9	<1	<1	<1
Sodium	3500	4290	4290	1940	1940	390	1900	610
Sulfate	548	815	815	815	815	26.4	12.7	38.6
Tantalum	0.3	0.3	0.5	2	0.8	0.5	0.9	0.2
Thallium	<0.2	0.7	1.7	1.3	1.7	<0.3	0.9	<0.3
Thorium	4.2	7.69	22.1	11.5	9.29	6.1	1.4	6.4
Thorium-Total	NA	37.1	30.1	25.9	16.3	15.6	19.9	NA
Uranium	0.4	1.39	5.93	2.48	1.64	0.9	0.2	0.6
Uranium-Total	NA	10.1	7.59	7.12	4.37	2.93	5.61	NA
Vanadium	3.8	1.67	4.01	4.01	4.01	9.5	2.8	29
Zinc	17	55.5	84.6	55.5	55.5	47	21	41

(a) - The maximum detected or non-detected value is reported for units Qct, Qbt 4, Qbo, and Tt. Readers are referred to Table VI for the derivation of the background screening values for Qbt1g1v23.
(1) - All values are in mg/kg unless otherwise noted.
(2) - Units are pCi/g.
ND - Not detected.
NA - Not available.

Inorganic Analytes

Aluminum (Al)

All of the 106 leachable aluminum concentrations were above ICPES detection limits. Square root transformed aluminum data are approximately normally distributed. Aluminum concentrations for all geologic units range from 350 to 14000 mg/kg and average 2187 mg/kg.

Population characteristics from the Wilcoxon rank sum test (Table IV) and box plots (Fig. 4) resulted in pooling the aluminum data for Qbt 1g, Qbt 2, and Qbt 3 (as Qbt 1g23) and Qbt 1v as a separate data group. Box plots comparing acid leachable aluminum by geologic unit show that medians, arithmetic means, and middle 50 percent ranges are distinctly greater for units Qbt 1v and Qbt 4 than for the other units (Fig. 4). Plots of leachable aluminum from individual stratigraphic sections show aluminum concentrations increase up section towards Qbt 1v before decreasing in the overlying tuffs (Fig. 5).

The background screening values for leachable aluminum are 4500 mg/kg for Tt, 1800 mg/kg for Qbo, 3400 mg/kg for Qct, 8170 mg/kg for Qbt 1v, 3700 mg/kg for Qbt 1g, Qbt 2, and Qbt 3, and 6200 mg/kg for Qbt 4. These background screening values are lower than the aluminum SAL of 77000 mg/kg.

Total aluminum concentrations by XRF and INAA tend to increase up section through the Tshirege Member (Fig. 5). Aluminum concentrations in the upper Otowi Member are slightly elevated with respect to the lower Tshirege Member. Comparison of acid leachable and total aluminum data for the Bandelier Tuff shows that approximately 10% to 25% of the total aluminum in the rock is leachable by nitric acid at a pH of 1.

Antimony (Sb)

Nine of the 106 leachable antimony concentrations were above ICPMS detection limits of 0.2 to 0.3 mg/kg. No statistical distribution of the antimony was estimated because of the limited number of detects. For samples above detection limits, leachable antimony concentrations range from 0.2 to 0.4 mg/kg and average 0.256 mg/kg.

The background screening values for leachable antimony are based on maximum detected concentrations in each rock unit. Background screening values are <0.3 mg/kg for Tt, <0.3 mg/kg for Qbo, 0.2 mg/kg for Qct, <0.3 mg/kg for Qbt 1g, 0.3 mg/kg for Qbt 1v, 0.3 mg/kg for Qbt 2, 0.4 mg/kg for Qbt 3, and <0.3 mg/kg for Qbt 4. Background screening values for antimony in all rock units are well below the SAL of 31 mg/kg for soils and rock.

Only two of 38 samples analyzed by INAA had total antimony concentrations above detection limits which ranged between 0.2 and 0.7 mg/kg. The maximum detected total antimony concentration was 0.7 mg/kg.

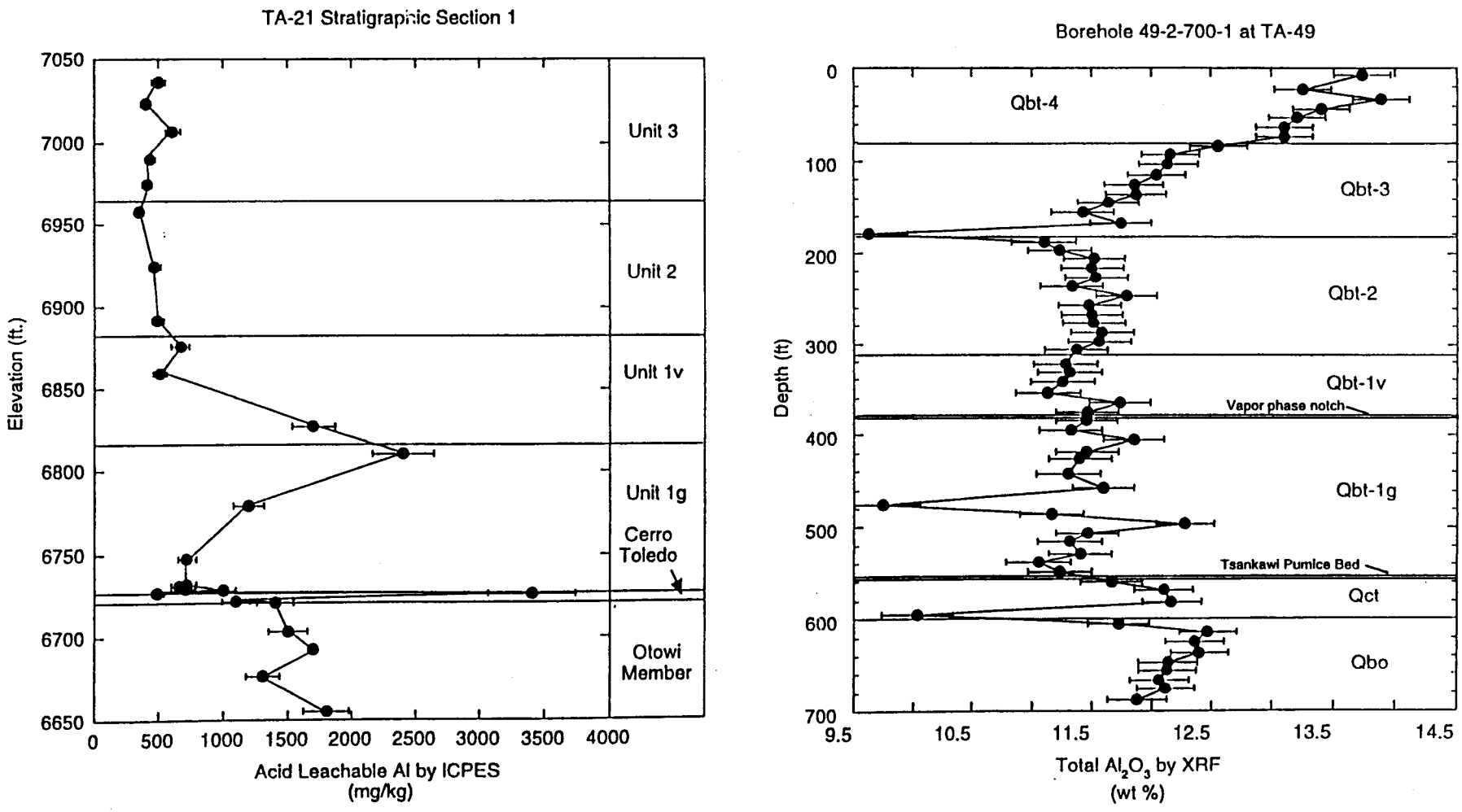


Fig. 5 Plots showing examples of acid leachable aluminum concentrations at TA-21 and total aluminum concentrations at TA-49 as a function of stratigraphic height in the Bandelier Tuff.

Arsenic (As)

Fifty-three of the 105 leachable antimony concentrations were above ETVAA detection limit of 0.5 mg/kg. No statistical distribution of the antimony was estimated because of the large number of non detects. For samples above detection limits, leachable antimony concentrations range from 0.5 to 5 mg/kg and average 1.08 mg/kg.

Box plots comparing acid leachable arsenic by geologic unit show that the middle 50 percent ranges are somewhat greater for units Qbt 3 and Qbt 4 than for the other units (Fig. 4). However, plots of leachable arsenic from individual stratigraphic sections fail to show any clear pattern of arsenic concentration variation as a function of stratigraphic height (Fig. 6).

The background screening values for leachable arsenic are based on maximum detected concentrations in each rock unit. Background screening values are <0.5 mg/kg for Tt, <0.5 mg/kg for Qbo, 0.5 mg/kg for Qct, 0.7 mg/kg for Qbt 1g, 2 mg/kg for Qbt 1v, 2 mg/kg for Qbt 2, 5 mg/kg for Qbt 3, and 2 mg/kg for Qbt 4. All of the background screening values exceed the SAL of 0.32 mg/kg.

Total arsenic concentrations by INAA were below detection limits for 61% of the samples. Concentrations ranged from 1.0 to 3.1 mg/kg for samples with total arsenic above the detection limit. Detection limits ranged from 1 to 4 mg/kg.

Barium (Ba)

All of the 106 leachable barium concentrations were above ICPES detection limits. Leachable barium data are approximately normally distributed. Barium concentrations for all geologic units range from 1.4 to 190 mg/kg and average 18.5 mg/kg.

Population characteristics from the Wilcoxon rank sum test (Table IV) and box plots (Fig. 4) resulted in pooling the barium data for Qbt 1g, Qbt 1v, Qbt 2, and Qbt 3 (as Qbt 123). Box plots comparing acid leachable barium by geologic unit show that medians, arithmetic means, and middle 50 percent ranges are greater for units Tt and Qbt 4 than for the other units (Fig. 4). Plots of leachable barium at individual stratigraphic sections supports the pooling of the leachable data set Qbt 123 (Fig. 7).

The background screening values for leachable barium are 69 mg/kg for Tt, 23 mg/kg for Qbo, 18 mg/kg for Qct, 42 mg/kg for Qbt 4, and 28 mg/kg for Qbt 1g, Qbt 1v, Qbt 2, and Qbt 3. Background screening values for barium in these rock units are well below the SAL of 5300 mg/kg.

Total barium concentrations by XRF tend to increase up section through the Tshirege Member (Fig. 7). The highest concentrations of total barium occur in Qbt 4 which contains about three times as much barium as the base of the Tshirege Member. Barium concentrations in the upper Otowi Member are about twice that found in the lower Tshirege Member. Comparison of acid leachable and total barium data for the Bandelier Tuff shows that approximately 5 to 30% of the total barium in the rock is leachable by nitric acid at a pH of 1.

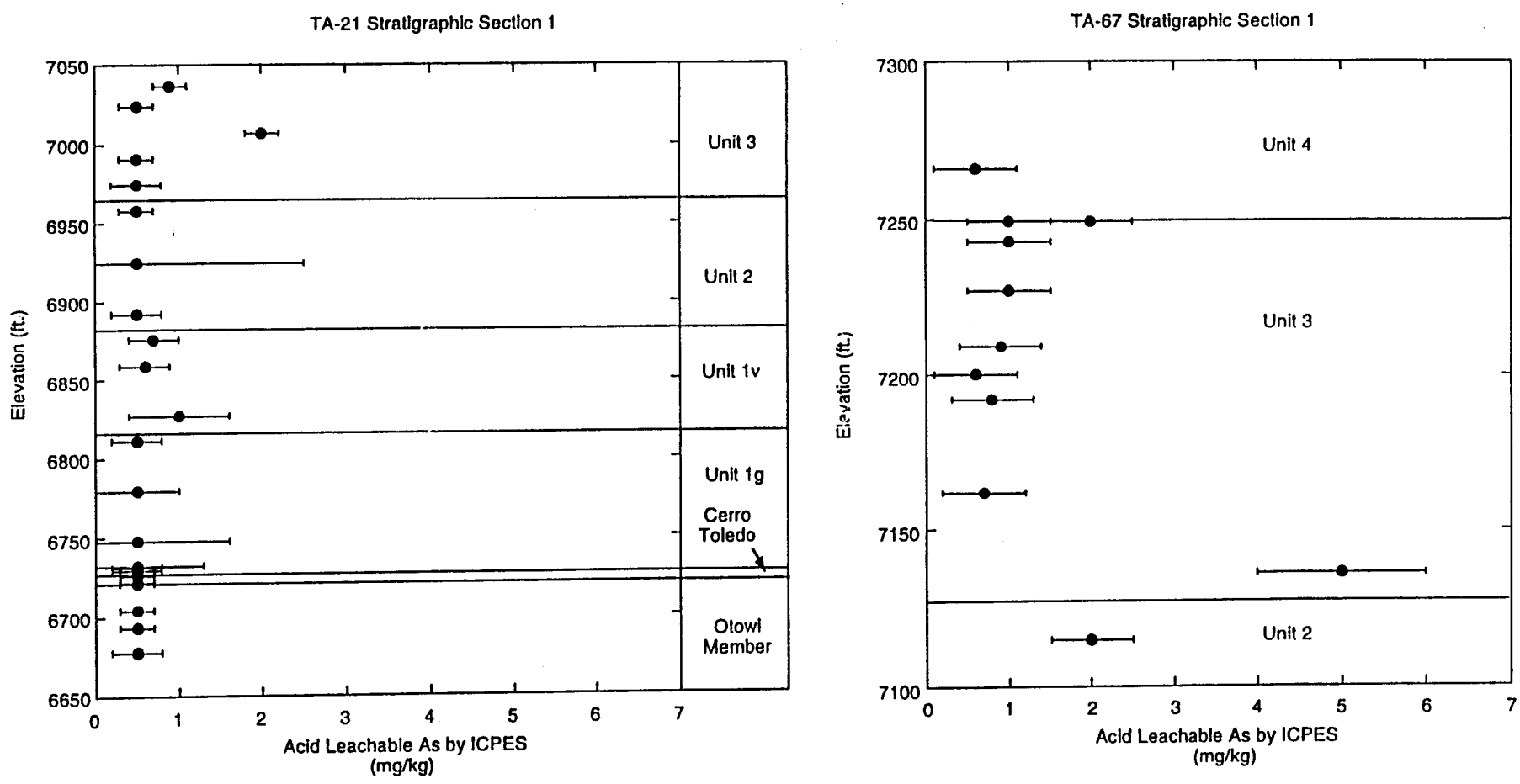


Fig. 6 PLOTS SHOWING EXAMPLES OF ACID LEACHABLE ARSENIC CONCENTRATIONS AS A FUNCTION OF STRATIGRAPHIC HEIGHT IN THE BANDELIER TUFF AT TA-21 AND TA-67.

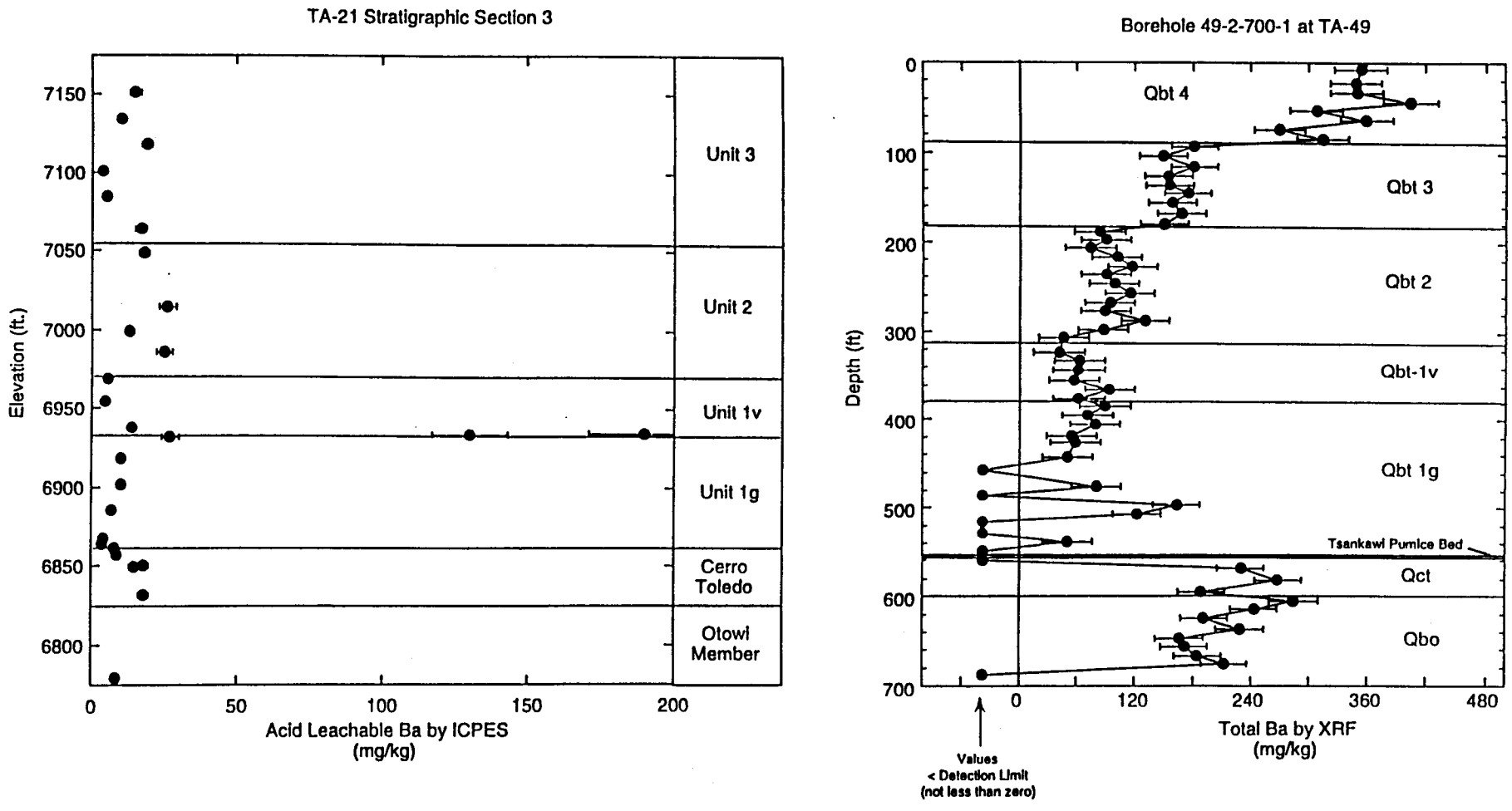


Fig. 7 Plots showing examples of acid leachable barium concentrations at TA-21 and total barium concentrations at TA-49 as a function of stratigraphic height in the Bandelier Tuff. Note the enrichment of leachable barium associated with the Qbt 1g/Qbt 1v contact in stratigraphic section 3 at TA-21. This barium enrichment is a local phenomena associated with secondary alteration at the vapor phase notch. Its is represented by samples 1106-3-12, 1106-3-13, and 1106-3-14.

Beryllium (Be)

Ninety-three of the 106 leachable beryllium concentrations were above ICPES detection limits of 0.0 to 0.14 mg/kg. Square root transformed beryllium data are approximately normally distributed. For samples above detection limits, beryllium concentrations for all geologic units range from 0.15 to 3.4 mg/kg and average 0.70 mg/kg.

Population characteristics from the Wilcoxon rank sum test (Table IV) resulted in pooling the beryllium data for Qbt 1g, Qbt 1v, Qbt 2, and Qbt 3 (as Qbt 123). Box plots comparing acid leachable beryllium by geologic unit show that medians, arithmetic means, and middle 50 percent ranges are generally less for units Tt, Qbo, Qct, Qbt 3 and Qbt 4 than for the other units (Fig. 4). Plots of leachable beryllium from individual stratigraphic sections show that in the Tshirege Member, beryllium concentrations increase up section from the base of the unit towards the Qbt 1g/Qbt 1v contact before decreasing in the overlying tuff units (Fig. 8). Enrichment of leachable beryllium at the Qbt 1g/Qbt 1v contact coincides with the vapor phase notch that separates two units. The vapor phase notch frequently has an unusual geochemistry suggestive of secondary alteration concentrated along a boundary of contrasting rock lithologies.

The background screening values for leachable beryllium are 0.21 mg/kg for Tt, 1.2 mg/kg for Qbo, 0.95 mg/kg for Qct, 1.8 mg/kg for Qbt 4, and 1.53 mg/kg for Qbt 1g, Qbt 1v, Qbt 2, and Qbt 3. All of the background screening values exceed the SAL of 0.14 mg/kg.

Total beryllium concentrations by INAA decrease up section through the Tshirege Member (Fig. 8). The highest concentrations of total beryllium occur in units Qbt 1g and Qbt 1v which contain approximately twice as much beryllium as units 3 and 4. Beryllium concentrations in the upper Otowi Member are slightly lower than those found in the lower part of the Tshirege Member. Comparison of acid leachable and total beryllium data for the Bandelier Tuff shows that approximately 15 to 50% of the total beryllium in the rock is leachable by nitric acid at a pH of 1.

Cadmium (Cd)

Leachable cadmium concentrations were not determined for this investigation because total cadmium was not detected in the samples analyzed by INAA. All 38 of the samples analyzed by INAA had total cadmium concentrations below the detection limit of 1 mg/kg. Thus naturally cadmium concentrations are well below the SAL of 38 mg/kg.

Calcium (Ca)

All of the 106 leachable calcium concentrations were above ICPES detection limits. Log transformed calcium data are approximately normally distributed. Calcium concentrations for all geologic units range from 200 to 4800 mg/kg and average 825 mg/kg.

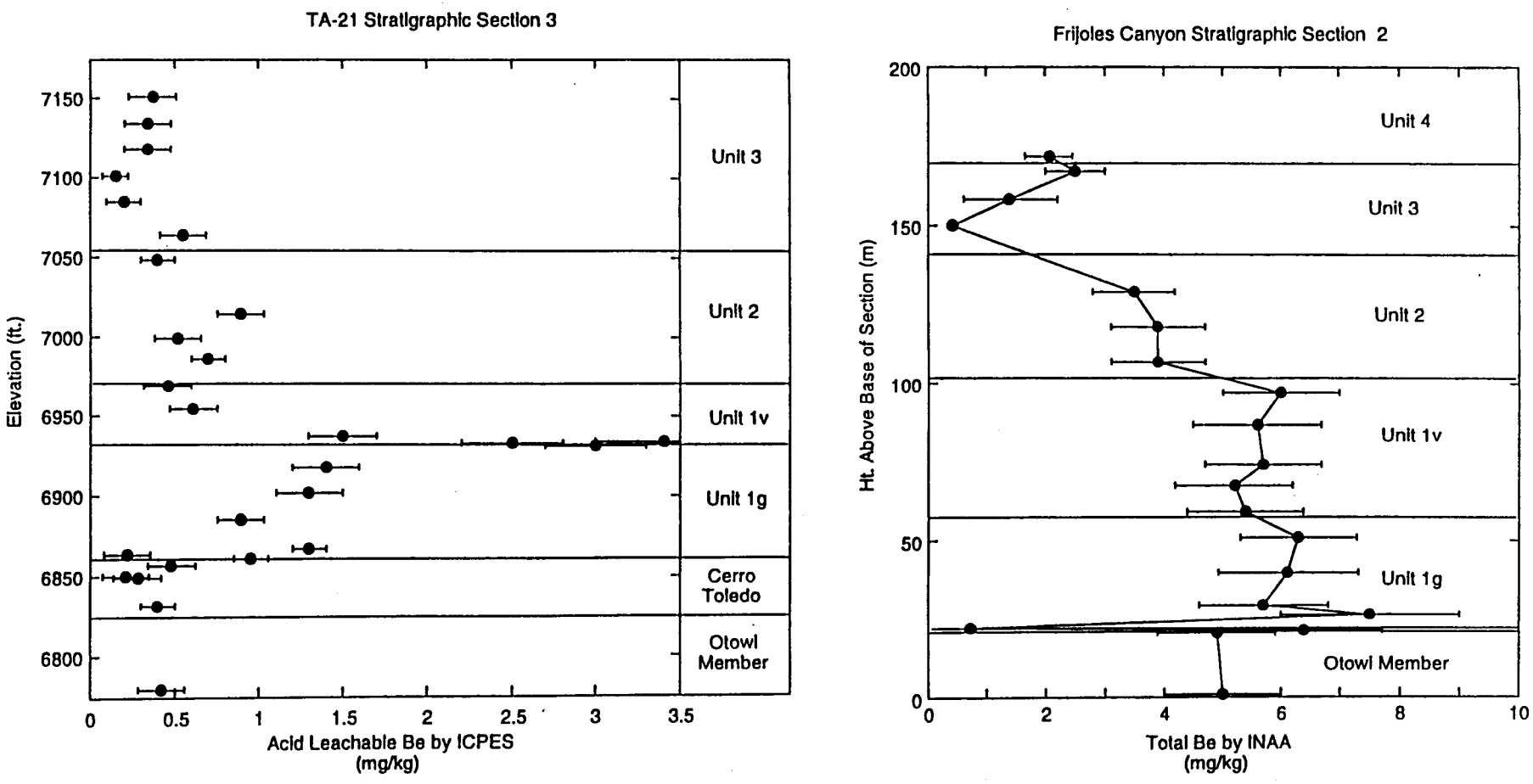


Fig. 8 PLOTS SHOWING EXAMPLES OF ACID LEACHABLE BERYLLIUM CONCENTRATIONS AT TA-21 AND TOTAL BERYLLIUM CONCENTRATIONS AT FRIJOLES CANYON AS A FUNCTION OF STRATIGRAPHIC HEIGHT IN THE BANDELIER TUFF.

Population characteristics from the Wilcoxon rank sum test (Table IV) resulted in pooling the calcium data for Qbt 1g and Qbt 1v (as Qbt 1) and pooling the calcium data for Qbt 2 and Qbt 3 (as Qbt 23). Box plots comparing acid leachable calcium by geologic unit show that medians, arithmetic means, and middle 50 percent ranges are generally greater for units Tt and Qbt 4 than for the other units (Fig. 4). Plots of leachable calcium from individual stratigraphic sections show that in the Tshirege Member, calcium concentrations are highly variable, particularly in units Qbt 1g and Qbt 1v (Fig. 9). The greatest enrichments or depletions of leachable calcium seem to be associated with unit boundaries and may represent secondary alteration along preferential ground water pathways.

The background screening values for leachable calcium are 2700 mg/kg for Tt, 890 mg/kg for Qbo, 1500 mg/kg for Qct, 4140 mg/kg for Qbt 1g and Qbt 1v, 1520 mg/kg for Qbt 2 and Qbt 3, and 1800 for Qbt 4.

Except for higher concentrations in Qbt 4, total calcium concentrations by XRF and INAA are relatively constant in the Tshirege Member (Fig. 9). Calcium concentrations in the upper Otowi Member tend to increase up section, and they are slightly elevated with respect to the lower Tshirege Member. Because of its low abundance, calcium concentrations in the Bandelier Tuff are easily affected by diagenetic alteration, particularly in the near-surface environment and near fractures where calcite ($CaCO_3$) is commonly deposited by infiltrating ground water.

Chlorine (Cl)

Leachable chlorine concentrations were determined for rock samples on aliquots extracted in deionized water and analyzed by IC. All of the 106 leachable chlorine concentrations were above detection limits. Log transformed chlorine data are approximately normally distributed. Chlorine concentrations for all geologic units range from 3.65 to 802 mg/kg and average 59.9 mg/kg.

Population characteristics from the Wilcoxon rank sum test (Table IV) resulted in pooling the chlorine data for Qbt 1g and Qbt 1v (as Qbt 1), and Qbt 2 and Qbt 3 were each treated as separate data groups. Box plots comparing leachable chlorine by geologic unit show that chlorine concentration ranges are distinctly greater for units Tt and Qbt 4 than for the other units (Fig. 4). Plots of leachable chlorine from individual stratigraphic sections show that leachable chlorine concentrations vary little throughout the Otowi and Tshirege Members with the exception of high chlorine concentrations along some unit contacts (e.g., Fig. 10).

Particularly high concentrations of soluble chlorine are associated with the lower Tshirege Member (including the Tsankawi Pumice Bed) and the tephras and volcaniclastic sediments of the Cerro Toledo interval in stratigraphic section 1 at TA-21 (Fig. 10). The presence of elevated chlorine concentrations in these tuffs suggests that they acted as preferential ground water pathways at some time after their deposition. These tuffs are now well above the canyon floor and there is no evidence of present-day ground water perching in these units. Most likely these units were preferential ground water pathways when Los Alamos Canyon was shallower, and these units were below the level of potential perched alluvial ground water bodies on the canyon floor.

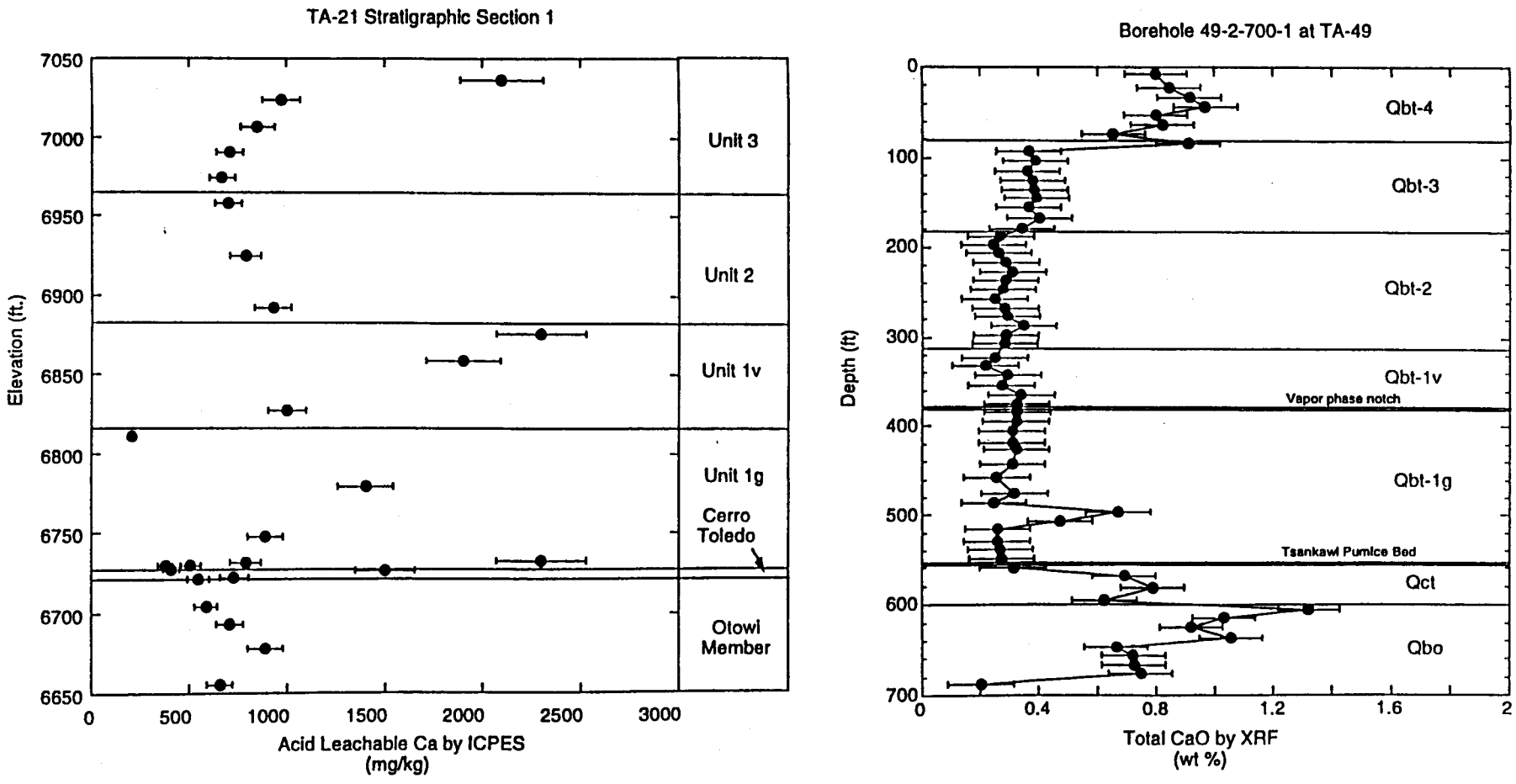


Fig. 9 PLOTS SHOWING EXAMPLES OF ACID LEACHABLE CALCIUM CONCENTRATIONS AT TA-21 AND TOTAL CALCIUM CONCENTRATIONS AT FRIJOLES CANYON AS A FUNCTION OF STRATIGRAPHIC HEIGHT IN THE BANDELIER TUFF.

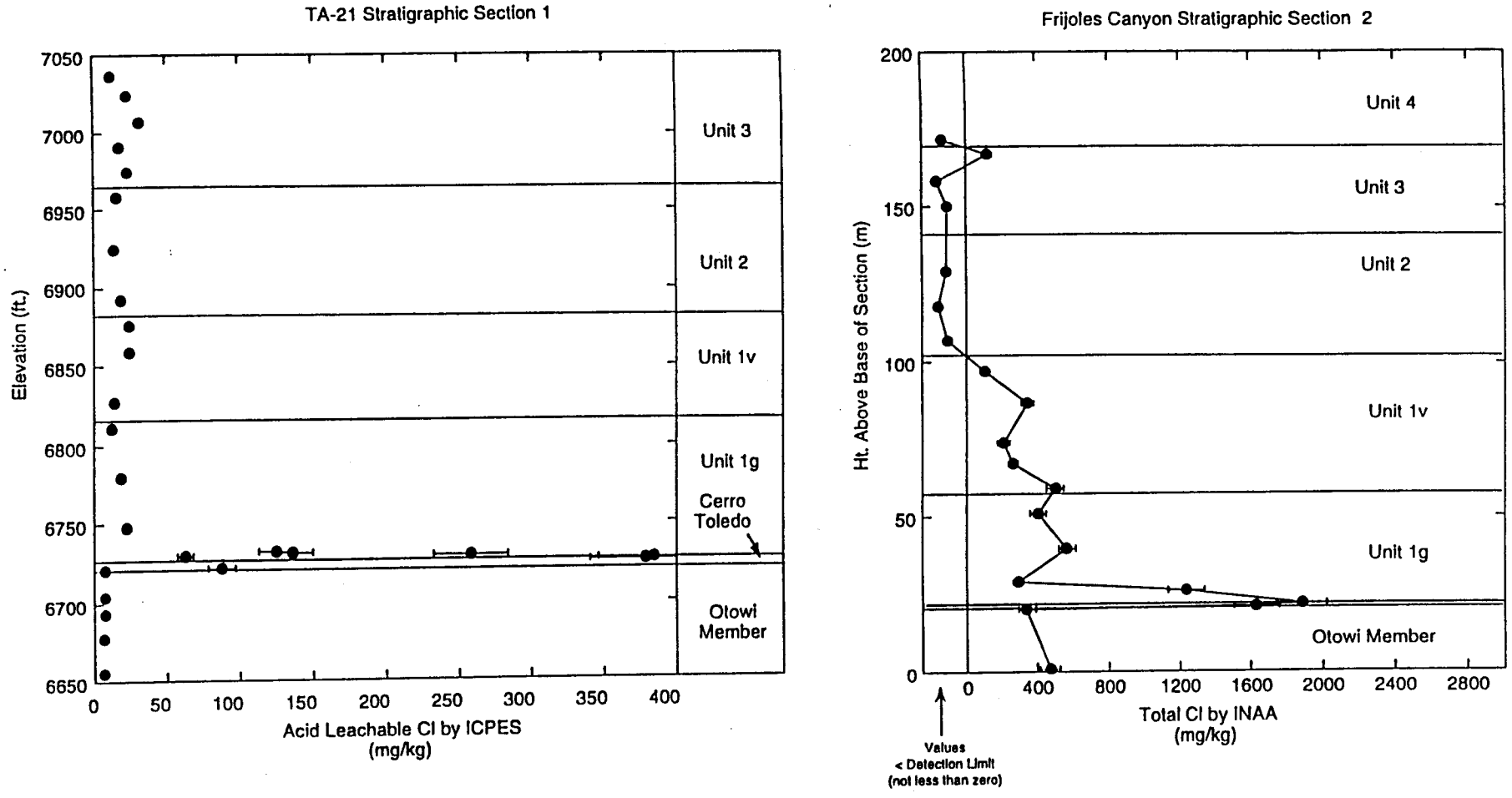


Fig. 10 PLOTS SHOWING EXAMPLES OF ACID LEACHABLE CHLORINE CONCENTRATIONS AT TA-21 AND TOTAL CHLORINE CONCENTRATIONS AT FRIJOLES CANYON AS A FUNCTION OF STRATIGRAPHIC HEIGHT IN THE BANDELIER TUFF.

In addition to the vertical variations in leachable chlorine concentrations described above, there are also lateral variations in leachable chlorine across the Pajarito Plateau (Fig. 11). Median leachable chlorine concentrations for the Bandelier Tuff typically are 14 mg/kg in the central part of the Laboratory (e.g., TA-21, TA-67) and 44 mg/kg in the eastern part of the Laboratory. These lateral differences in median soluble Cl concentrations probably reflect increased evapotranspiration and/or decreased moisture flux within bedrock eastwards across the Laboratory due to higher average temperatures and to lower rain fall and snow fall.

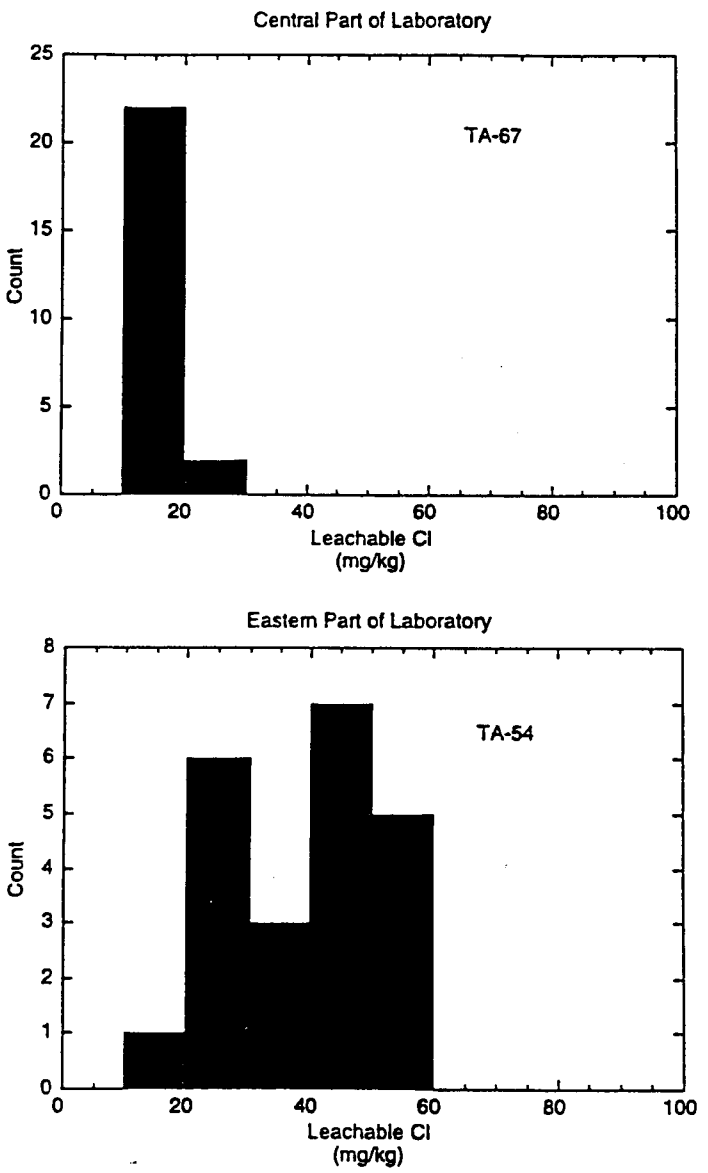


Fig. 11 Histogram of acid leachable chlorine concentrations in Bandelier Tuff as a function of lateral position. Chlorine concentrations generally increase eastward across the Pajarito Plateau. The few anomalous Cl concentrations above 100 mg/kg are not shown.

The background screening values for leachable chlorine are 67 mg/kg for Tt, 7.7 mg/kg for Qbo, 379 mg/kg for Qct, 405 mg/kg for Qbt 1g and Qbt 1v, 107 mg/kg for Qbt 2, 64.8 mg/kg for Qbt 3, and 14.9 mg/kg for Qbt 4. The background screening values are lower than the chlorine SAL of 7700 mg/kg.

Total chlorine concentrations by INAA systematically decrease up section from Qbt 1g to Qbt 4 in the Tshirege Member (Fig. 10). The highest total chlorine concentrations occur at the base of Qbt 1g and in the Tsankawi Pumice Bed. These high chlorine concentrations may represent secondary enrichment of chlorine by ground water along a preferential pathway. Chlorine concentrations are below detection limits in the upper part of Qbt 1v and in overlying units.

Chromium (Cr)

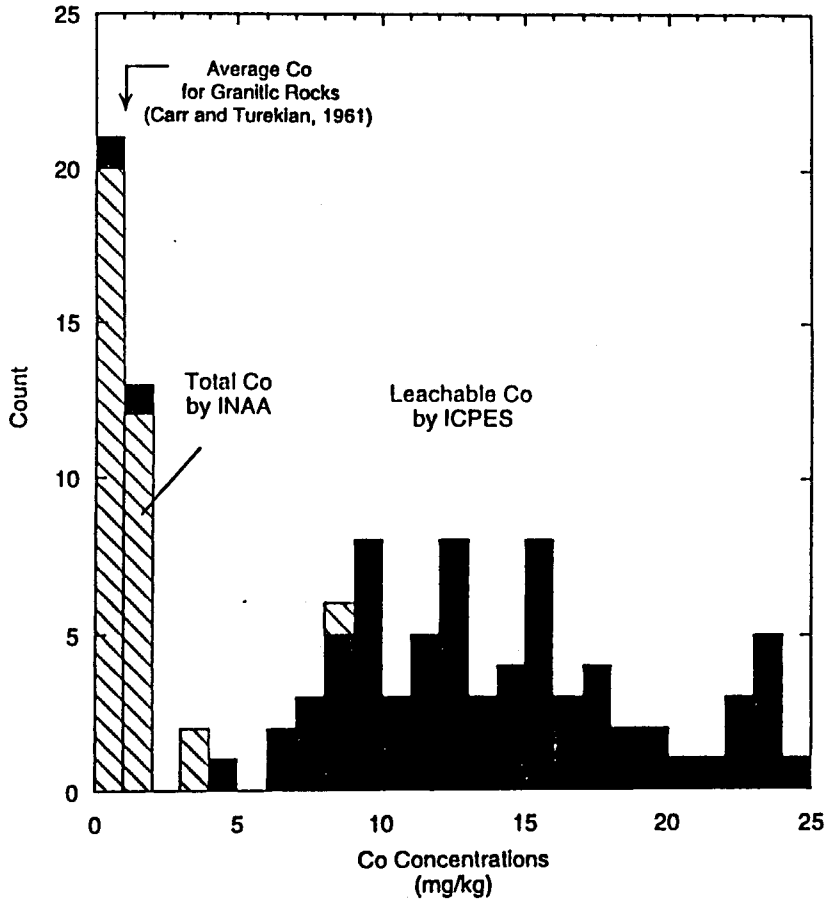
Sixty-eight of the 106 leachable chromium concentrations were above the ICPES detection limits of 0.5 to 2 mg/kg. No statistical distribution of the chromium was estimated because of the large number of non detects. For samples above detection limits, leachable chromium concentrations range from 0.57 to 10 mg/kg and average 1.70 mg/kg.

Box plots comparing acid leachable chromium by geologic unit show that the leachable chromium concentration ranges are greater for units Tt and Qbt 4 than for the other units (Fig. 4). The background screening values for leachable chromium are based on maximum detected concentrations in each rock unit. Background screening values are 10 mg/kg for Tt, 2.3 mg/kg for Qbo, 1.8 mg/kg for Qct, 0.94 mg/kg for Qbt 1g, 1.7 mg/kg for Qbt 1v, 1.6 mg/kg for Qbt 2, 2.1 mg/kg for Qbt 3, and 5.4 mg/kg for Qbt 4. Background screening values are less than the total chromium SAL of 210 mg/kg.

Cobalt (Co)

Artificially high concentrations of cobalt were introduced into the samples analyzed by ICPES during sample preparation. Cobalt contamination was added to the samples during powdering the samples in a tungsten-carbide shatter box. The median acid leachable cobalt in the Tshirege Member is 16 mg/kg. This median concentration is more than an order of magnitude greater than the median total cobalt value (0.85 mg/kg) determined by INAA (Fig. 12), and it is significantly greater than 1 mg/kg, the average cobalt value for rocks of granitic compositions (Carr and Turekian, 1961). Because of the potential for introduced contamination, we recommend that a ceramic shatter box be used to prepare rock samples for cobalt (and tungsten) analysis.

Because acid leachable cobalt concentrations by ICPES are suspected of being in error, background screening levels for cobalt in the Bandelier Tuff (Table VII) are based on the maximum total cobalt concentration for each unit. Total concentrations were determined by INAA for samples powdered in a ceramic shatter box. Total cobalt concentrations by INAA range from <0.3 to 8.8 mg/kg and average 1.3 mg/kg. Total cobalt values are relatively constant in the Tshirege Member, except for a single cobalt determination for Qbt 4 which was



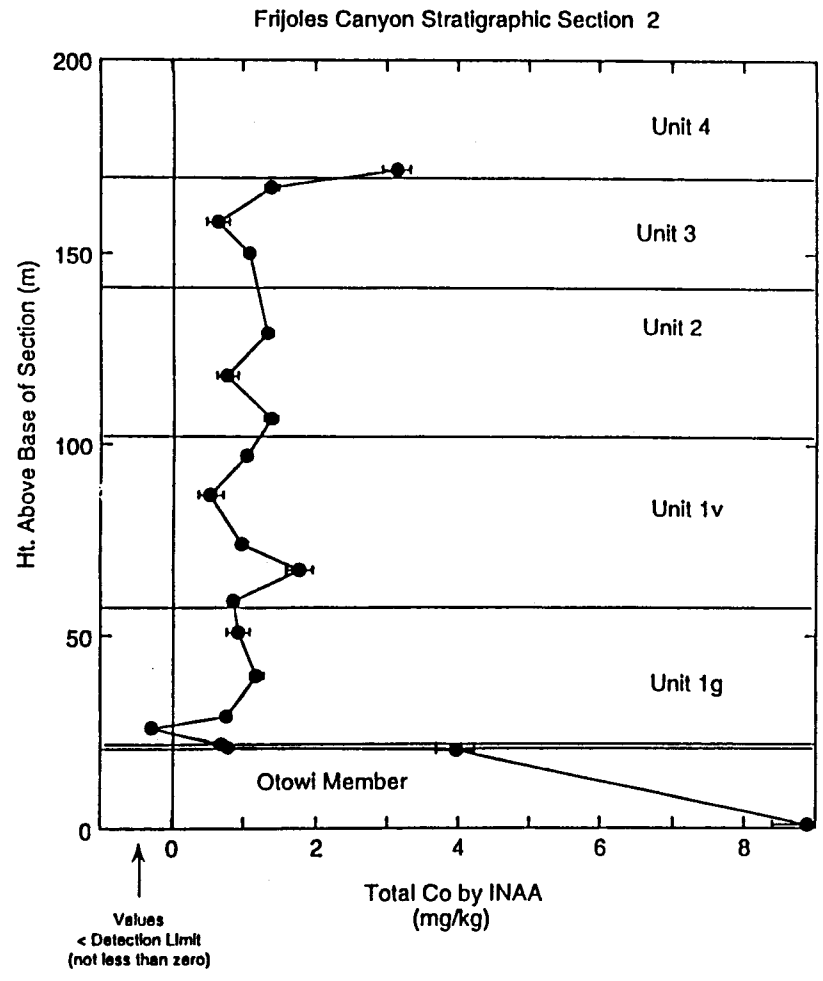


Fig. 12 On left, histogram of total Co concentrations by INAA vs leachable cobalt concentrations by ICPES for the Bandelier Tuff (outliers above 25 mg/kg not shown). On right, total cobalt concentrations at Frijoles Canyon as a function of stratigraphic height in the Bandelier Tuff. Because of probable analytical errors, leachable cobalt values are not used to determine background screening values.

three times greater than the underlying tuffs (Fig. 12). The highest concentrations of total cobalt occur in two samples of Qbo. The two cobalt determinations for Qbo are four to eight times greater than those in Qbt 1g.

Background screening values are 8.8 mg/kg for Qbo, 1.27 mg/kg for Qbt 1g, 1.78 mg/kg for Qbt 1v, 1.38 mg/kg for Qbt 2, 1.39 mg/kg for Qbt 3, and 3.14 mg/kg for Qbt 4.

Copper (Cu)

Fifty-seven of the 106 leachable copper concentrations were above the ICPES detection limits of 0.5 to 2 mg/kg. No statistical distribution of the copper was estimated because of the large number of non detects. For samples above detection limits, leachable copper concentrations range from 0.6 to 16 mg/kg and average 2.38 mg/kg.

Box plots comparing acid leachable copper by geologic unit show that the leachable copper concentration ranges are relatively constant for all rock units except for Tt, which has distinctly greater concentrations of leachable copper than the other units (Fig. 4). The background screening values for leachable copper are based on maximum detected concentrations in each rock unit. Background screening values are 16 mg/kg for Tt, 2.6 mg/kg for Qbo, 2.2 mg/kg for Qct, 2.4 mg/kg for Qbt 1g, 2.6 mg/kg for Qbt 1v, 2 mg/kg for Qbt 2, 2 mg/kg for Qbt 3, and 1.6 mg/kg for Qbt 4. Background screening values for leachable copper in the Bandelier Tuff are well below the SAL of 2800 mg/kg.

Total copper concentrations by INAA for the Bandelier Tuff were below the detection limits, which ranged from about 250 to 400 mg/kg. These detection limits are much greater than average copper concentrations in granitic rocks of about 10 mg/kg (Turekian and Wedepohl, 1961).

Iron (Fe)

All of the 106 leachable iron concentrations were above ICPES detection limits. Iron concentrations for all geologic units range from 190 to 13000 mg/kg and average 3867 mg/kg.

Population characteristics from the Wilcoxon rank sum test (Table IV) resulted in pooling the leachable iron data for Qbt 1g as one data group and pooling the data for Qbt 1v, Qbt 2 and Qbt 3 (as Qbt 1v23) as another data group. Each data group was bimodally distributed. Box plots comparing acid leachable iron by geologic unit show that medians, arithmetic means, and middle 50 percent ranges are generally greater for units Tt and Qbt 4 than for the other units (Fig. 4). The distribution of acid leachable iron concentrations in the Tshirege Member is complex. The greatest concentrations of acid leachable iron occur at the Qbt 1g/Qbt 1v contact, and generally iron concentrations decrease up section (Fig. 13). In contrast to iron in stratigraphic section 1 at TA-21 (Fig. 13), relatively high concentrations of leachable iron occur up section to the top of Qbt 2 in stratigraphic section 3 at TA-21.

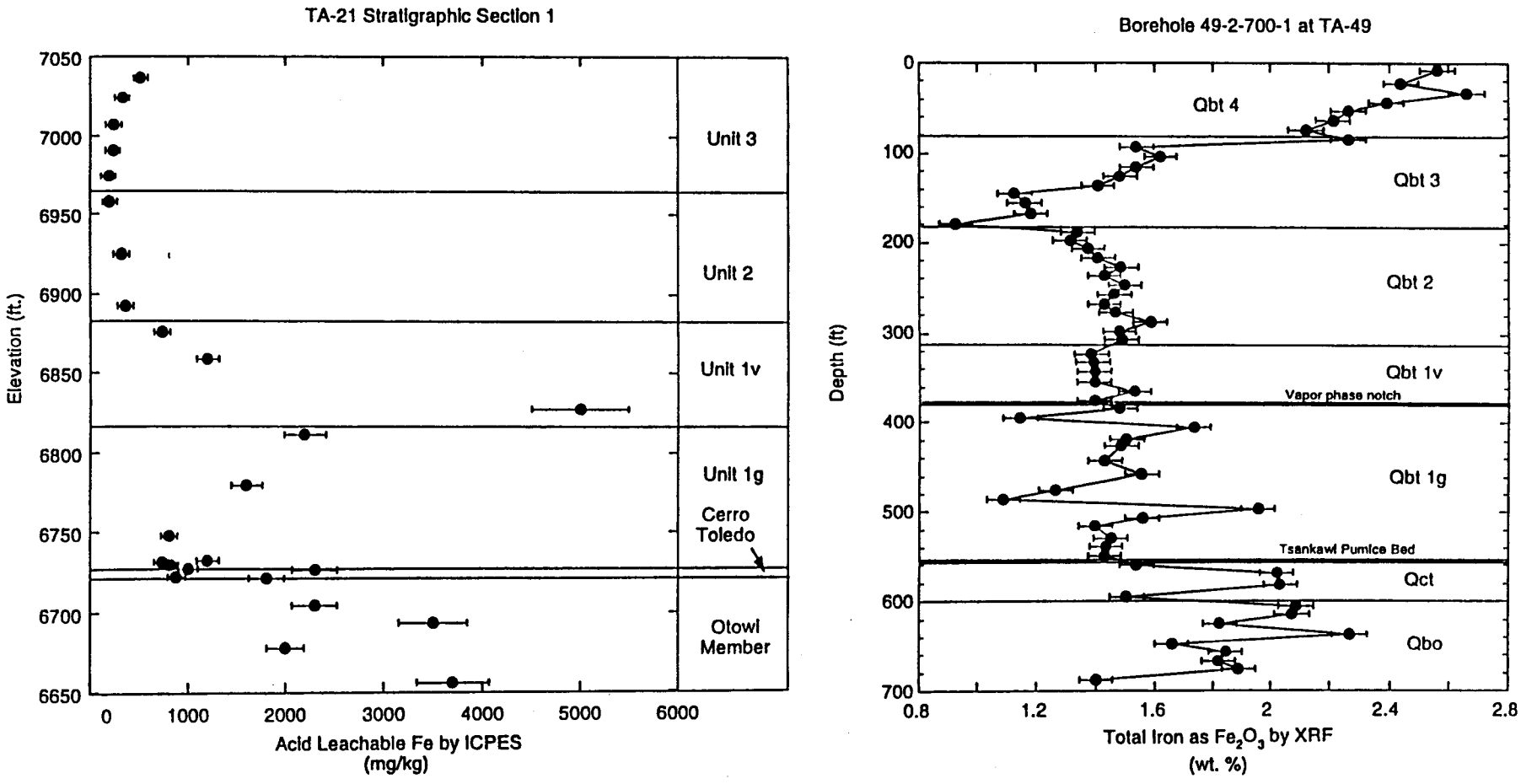


Fig. 13 PLOTS SHOWING EXAMPLES OF ACID LEACHABLE IRON CONCENTRATIONS AT TA-21 AND TOTAL IRON CONCENTRATIONS AT TA-49 AS A FUNCTION OF STRATIGRAPHIC HEIGHT IN THE BANDELIER TUFF.

Instead of estimating a mixture distribution because of the bimodality in each data group, we use the maximum leachable iron concentration for each data group for the background screening values. The background screening values are 13000 mg/kg for Tt, 3700 mg/kg for Qbo, 2400 mg/kg for Qct, 3250 mg/kg for Qbt 1g, 12000 mg/kg for Qbt 4, and 9040 mg/kg for Qbt 1v, Qbt 2 and Qbt 3.

Total iron concentrations by XRF and INAA vary little in Qbt 1g, Qbt 1v, and Qbt 2 (Fig. 13). Total iron concentrations initially decrease up section across the Qbt 2/Qbt 3 contact, but then increase up section through Qbt 3. Total iron concentrations increase abruptly across the Qbt 3/Qbt 4 contact and concentrations increase up section through Qbt 4. The top of Qbo contains about twice as much total iron as the Qbt 1g tuffs at the base of the Tshirege Member (Fig. 13).

Lead (Pb)

All of the 106 leachable lead concentrations were above ICPMS detection limits. Square root transformed lead data are approximately normally distributed. Lead concentrations for all geologic units range from 0.6 to 36 mg/kg and average 6.95 mg/kg.

Population characteristics from the Wilcoxon rank sum test (Table IV) resulted in pooling all of the lead data for Qbt 1g, Qbt 1v, Qbt 2 and Qbt 3 (as Qbt 123). There was a significant between Qbt 1v and Qbt 1g, however this difference was not consistent with other Wilcoxon comparisons, which lead to pooling data across all data groups. Box plots comparing acid leachable lead by geologic unit show that medians, arithmetic means, and middle 50 percent ranges are generally greater for unit Qbt 1v than for the other units (Fig. 4). Plots of leachable lead from individual stratigraphic sections show that in the Tshirege Member, leachable lead concentrations are greatest in the center of the unit, particularly near the vapor phase notch at the unit Qbt 1g/Qbt 1v contact (Fig. 14).

The background screening values for leachable lead are 6.7 mg/kg for Tt, 5 mg/kg for Qbo, 7.1 mg/kg for Qct, 21.9 mg/kg for Qbt 1v, 4 mg/kg for Qbt 4, and 16.2 mg/kg for Qbt 1g, Qbt 2, and Qbt 3. Background screening values for lead in all rock units are well below the SAL of 400 mg/kg.

Total lead concentrations by INAA generally decrease up section in the Tshirege Member (Fig. 14). Two total lead concentrations were determined for Qbo; both were about 35% lower than total lead concentrations determined for Qbt 1g of the Tshirege Member. The percentage of total lead that is susceptible to acid leaching in the Bandelier Tuff varies with stratigraphic position. Approximately 25% to 75% of the lead near the Qbt 1g/Qbt 1v contact is released by leaching in a solution of nitric acid at a pH of 1. However, only 10% to 15% of the lead in the remainder of the Bandelier Tuff is dissolved by the nitric acid solution.

Magnesium (Mg)

All of the 106 leachable magnesium concentrations were above ICPES detection limits. Square root transformed magnesium data are approximately normally distributed. Magnesium concentrations for all geologic units range from 39 to 1700 mg/kg and average 296 mg/kg.

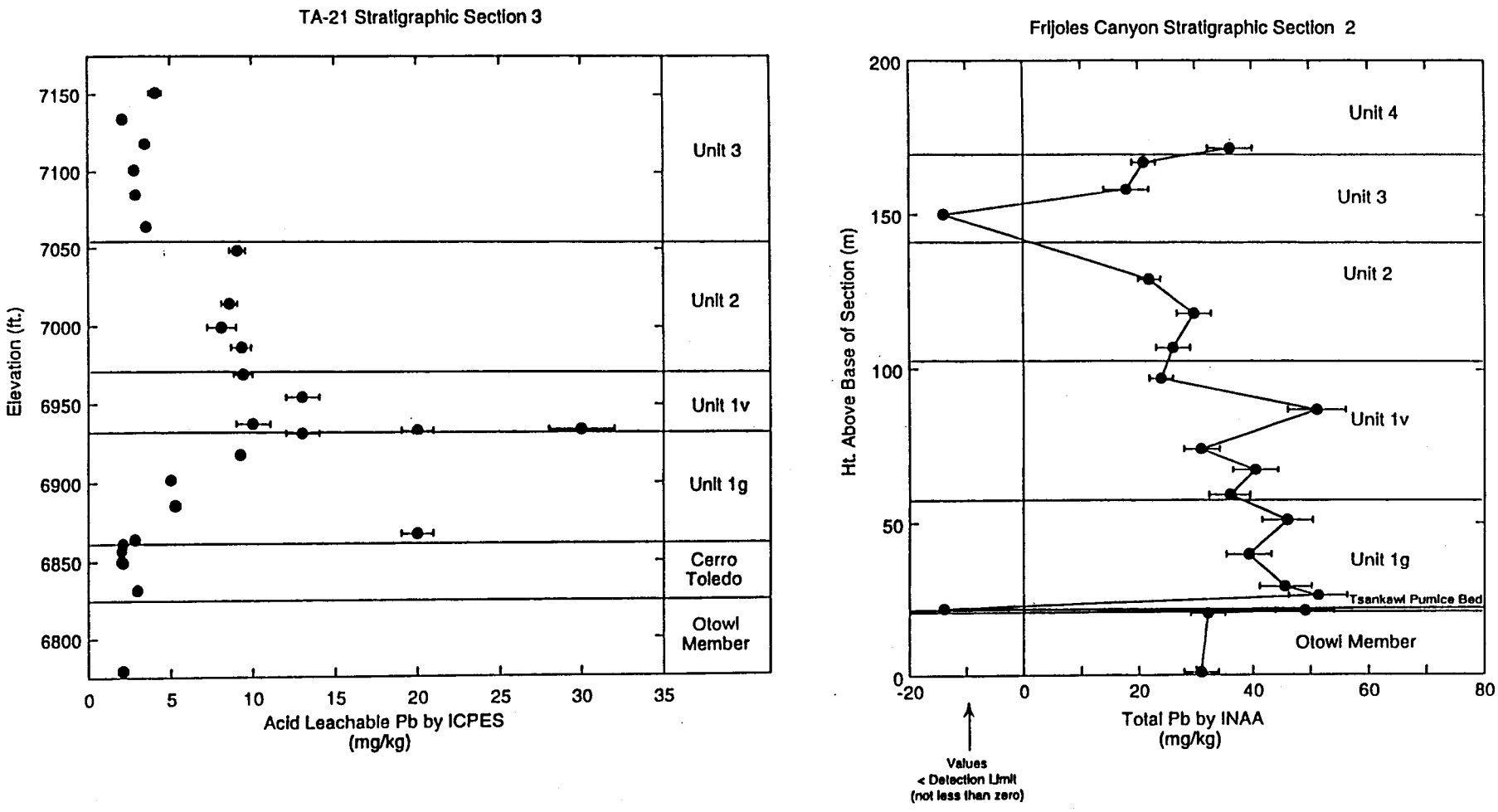


Fig. 14 Plots showing examples of acid leachable lead concentrations at TA-21 and total lead concentrations at Frijoles Canyon as a function of stratigraphic height in the Bandelier Tuff. Note the high concentrations of leachable lead associated with the contact between units Qbt 1g and Qbt 1v (vapor phase notch) represented by samples 1106-3-12, 1106-3-13, and 1106-3-14.

Population characteristics from the Wilcoxon rank sum test (Table IV) resulted in pooling all of the magnesium data for Qbt 1g and Qbt 2 (as Qbt1g2) and Qbt 1v and Qbt 3 (as Qbt 1v3). Box plots comparing acid leachable magnesium by geologic unit show that medians, arithmetic means, and middle 50 percent ranges are generally greater for units Tt and Qbt 4 than for the other units (Fig. 4). Plots of leachable magnesium from individual stratigraphic sections show no clear relation of concentrations to stratigraphic position (Fig. 15). Because of its low abundance and its chemical mobility, magnesium concentrations in the Bandelier Tuff are easily affected by diagenetic alteration, particularly in the near-surface environment.

The background screening values for leachable magnesium are 950 mg/kg for Tt, 510 mg/kg for Qbo, 510 mg/kg for Qct, 548 mg/kg for Qbt 1g and Qbt 2, 628 mg/kg for Qbt 1v and Qbt 3, and 1700 mg/kg for Qbt 4.

Although approximately half of the total magnesium concentrations by XRF and INAA are below detection limits, the greatest magnesium concentrations are clearly related to units Qbo and Qct (Fig. 15).

Manganese (Mn)

All of the 106 leachable manganese concentrations were above ICPES detection limits. Square root transformed manganese data are approximately normally distributed. Manganese concentrations for all geologic units range from 21 to 510 mg/kg and average 184 mg/kg.

Population characteristics from the Wilcoxon rank sum test (Table IV) resulted in pooling all of the manganese data for Qbt 1g as a data group, Qbt 1v and Qbt 2 as a data group (as Qbt1v2), and Qbt 3 as a data group. Box plots comparing acid leachable manganese by geologic unit show that medians, arithmetic means, and middle 50 percent ranges are generally greater for units Qbt 1v, Qbt 2, and Qbt 4 than for the other units (Fig. 4). Plots of leachable manganese from individual stratigraphic sections show that leachable manganese concentrations are greater in Qbt 1v and Qbt 2 than the rest of the Tshirege Member (Fig. 16).

The background screening values for leachable manganese are 280 mg/kg for Tt, 170 mg/kg for Qbo, 90 mg/kg for Qct, 273 mg/kg for Qbt 1g, 533 mg/kg for Qbt 1v and Qbt 2, 426 mg/kg for Qbt 3, and 370 mg/kg for Qbt 4. These background screening values are roughly equal to or greater than the manganese SAL of 380 mg/kg.

Total manganese concentrations by XRF and INAA vary little as a function of stratigraphic position (Fig. 16). There is a slight tendency for total manganese concentrations to decrease up section in the Tshirege Member, except for Qbt 4 which is characterized by an abrupt increase in manganese concentrations relative to underlying units. At TA-49, total manganese concentrations systematically decrease up section in the upper part of Qbo (Fig. 16).

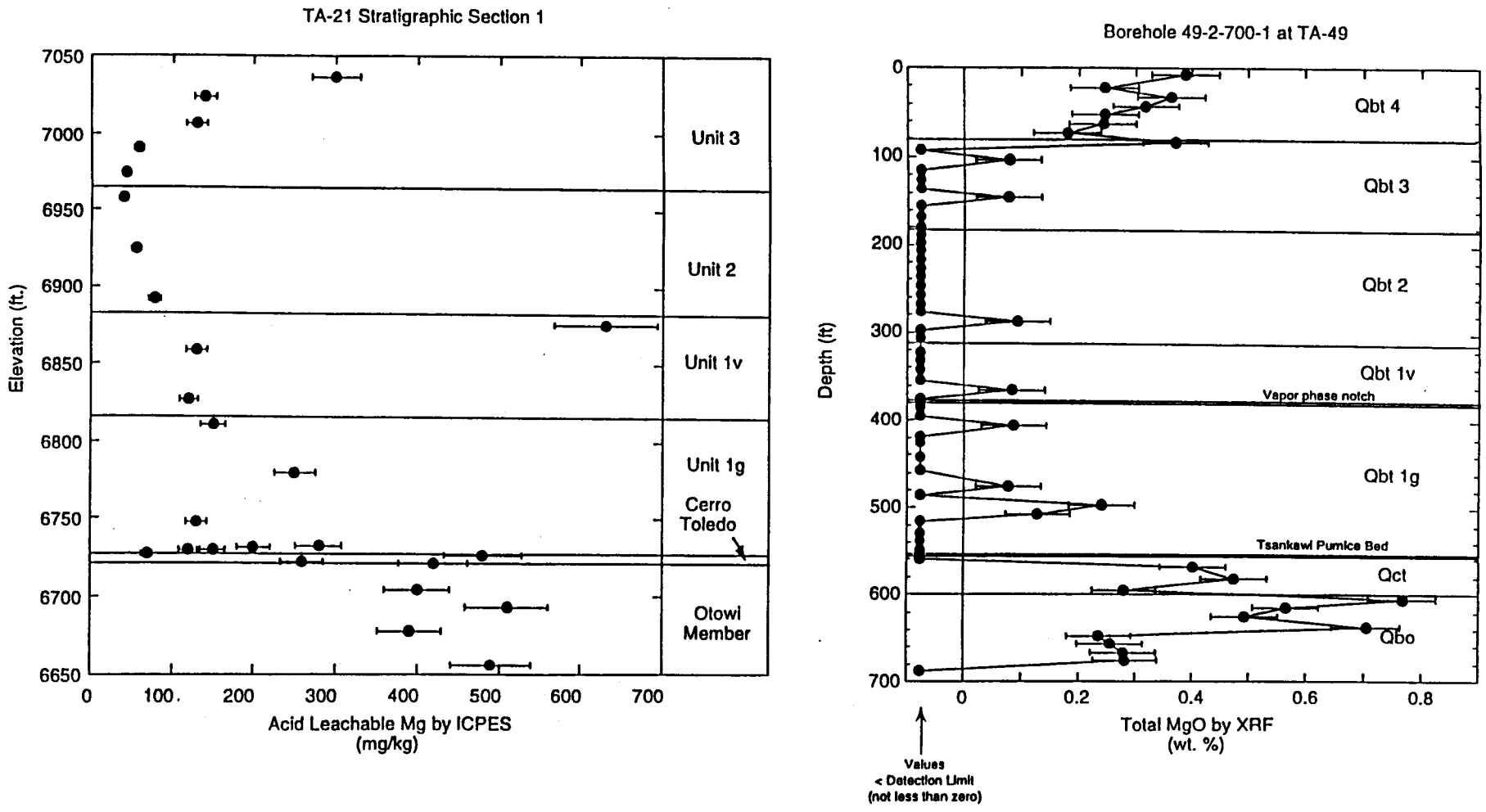


Fig. 15 PLOTS SHOWING EXAMPLES OF ACID LEACHABLE MAGNESIUM CONCENTRATIONS AT TA-21 AND TOTAL MAGNESIUM CONCENTRATIONS AT TA-49 AS A FUNCTION OF STRATIGRAPHIC HEIGHT IN THE BANDELIER TUFF.

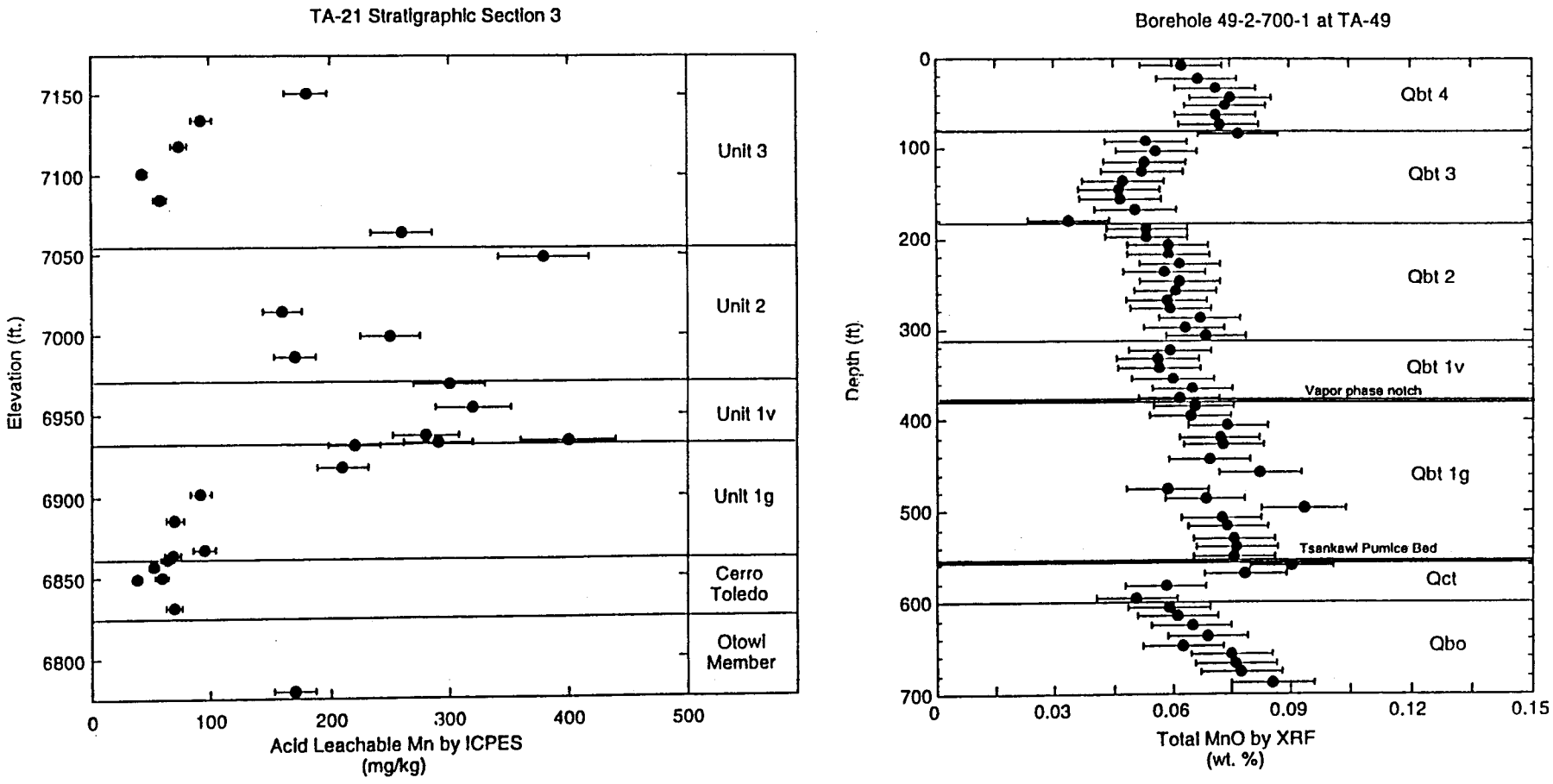


Fig. 16 PLOTS SHOWING EXAMPLES OF ACID LEACHABLE MANGANESE CONCENTRATIONS AT TA-21 AND TOTAL MANGANESE CONCENTRATIONS AT TA-49 AS A FUNCTION OF STRATIGRAPHIC HEIGHT IN THE BANDELIER TUFF.

Mercury (Hg)

Leachable mercury concentrations were not determined for this investigation because mercury was not detected in the INAA analyses. All 38 of the samples analyzed by INAA had total mercury concentrations below detection limits, which range from 0.3 to 0.7 mg/kg. Thus naturally mercury concentrations are well below the SAL of 23 mg/kg.

Nickel (Ni)

Only 9 of the 106 leachable nickel concentrations were above ICPES detection limits of 1 to 2 mg/kg. No statistical distribution of the nickel was estimated because of the large number of non detects. For samples above detection limits, leachable nickel concentrations range from 2 to 15 mg/kg and average 4.6 mg/kg.

Box plots comparing acid leachable nickel by geologic unit show that the highest leachable nickel concentrations are associate with unit Tt (Fig. 4). The background screening values for leachable nickel are based on maximum detected concentrations in each rock unit. Background screening values are 15 mg/kg for Tt, 2.8 mg/kg for Qbo, <2 mg/kg for Qct and Qbt 1g, 2 mg/kg for Qbt 1v, <2 mg/kg for Qbt 2, 2.6 mg/kg for Qbt 3, and <2 mg/kg for Qbt 4. Background screening values for all rock units are well below the SAL of 1500 mg/kg.

Total nickel concentrations by XRF were generally below detection limits which ranged between 6 and 7 mg/kg.

Potassium (K)

All of the 106 leachable potassium concentrations were above ICPES detection limits. Square root transformed potassium data are approximately normally distributed. Potassium concentrations for all geologic units range from 250 to 5400 mg/kg and average 1055 mg/kg.

Population characteristics from the Wilcoxon rank sum test (Table IV) resulted in pooling all of the potassium data for Qbt 1g and Qbt 2 (as data group Qbt 1g2). Qbt 1v and Qbt 3 were pooled as two separate data groups. Box plots comparing acid leachable potassium by geologic unit show generally high concentrations for units Qbt 1g and generally low concentrations for units Qbo, Qbt 3, and Tt (Fig. 4). Plots of leachable potassium from individual stratigraphic sections show that leachable potassium concentrations are greatest in the glassy tuffs (units Qbo, Qct, and Qbt 1g), and concentrations decrease up section in the overlying devitrified tuffs (Fig. 17).

The background screening values for leachable potassium are 1100 mg/kg for Tt, 960 mg/kg for Qbo, 1600 mg/kg for Qct, 2730 mg/kg for Qbt 1g and Qbt 2, 5540 mg/kg for Qbt 1v, 735 mg/kg for Qbt 3, and 1600 mg/kg for Qbt 4.

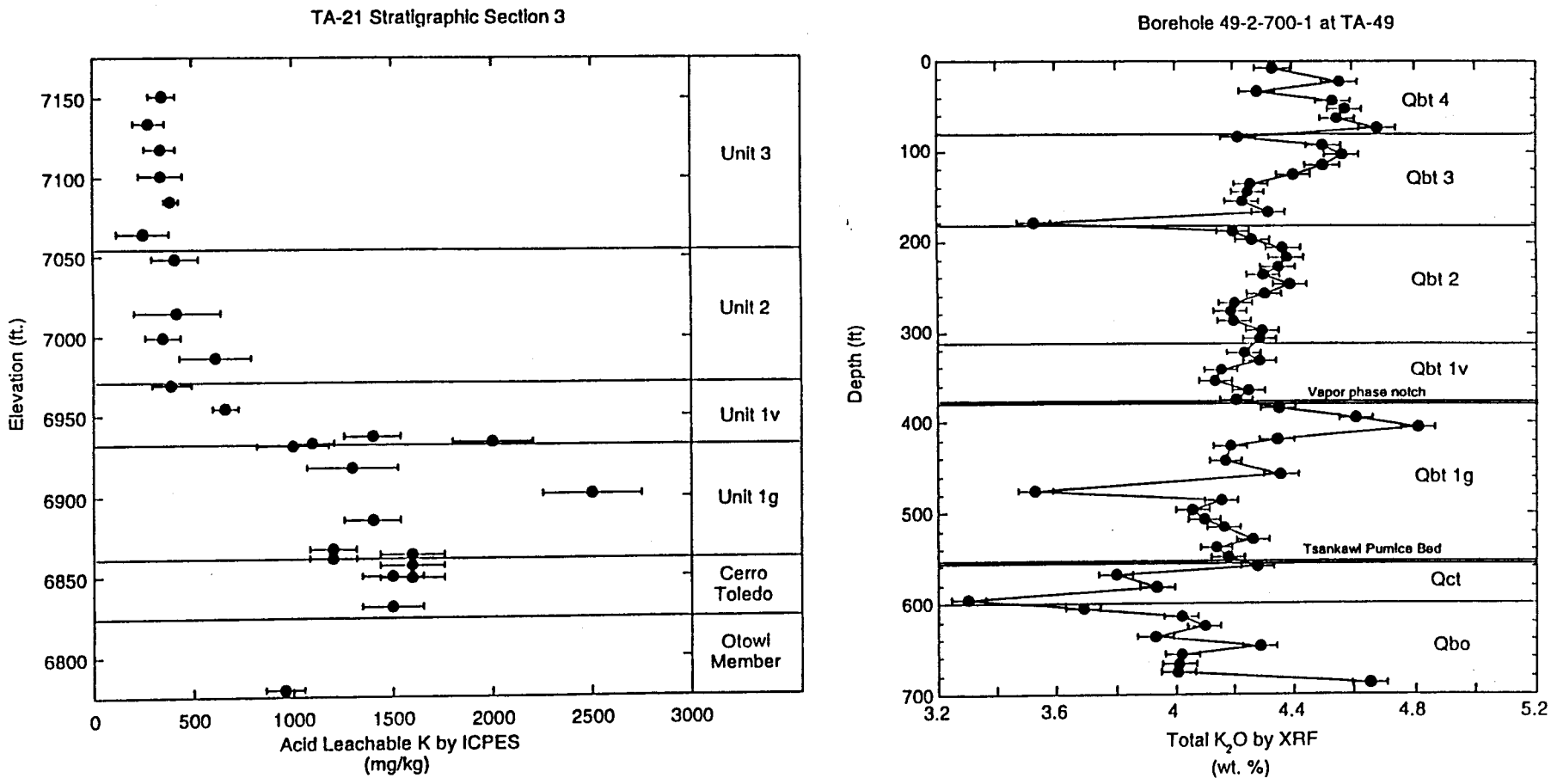


Fig. 17 Plots showing examples of acid leachable potassium concentrations at TA-21 and total potassium concentrations at TA-49 as a function of stratigraphic height in the Bandelier Tuff.

There is slight increase up section in total potassium concentrations by XRF and INAA in the Bandelier Tuff. Increasing total potassium up section is opposite of the general decrease in soluble potassium up section in the Tshirege Member (Fig. 17). Total potassium concentrations at the top of Qbo are somewhat lower than those found in the basal tuffs of the Tshirege Member (e.g., Qbt 1g). Potassium in the Bandelier Tuff is relatively insoluble, and only 1% to 10% of the total potassium in the rock is released by leaching in a solution of nitric acid at a pH of 1.

Selenium (Se)

Leachable selenium concentrations were not determined for this investigation because total selenium was not detected by INAA, and these detection limits were consistently less than the SAL. All 38 of the samples analyzed by INAA had total selenium concentrations below detection limits, which range from 1.1 to 4.9 mg/kg. Thus leachable selenium concentration should be well below the SAL of 380 mg/kg.

Silver (Ag)

Only 1 of the 106 leachable silver concentrations was above ICPES detection limits of 1 to 2 mg/kg. The single detected silver concentration, which occurred in unit Qbt 3, was 1.9 ± 1.0 mg/kg.

Except for unit Qbt 1v, background screening values for leachable silver are based on maximum detection limits in each rock unit. Background screening values are <1 mg/kg for Tt, Qbo, Qct, Qbt 2, and Qbt 4, <2 mg/kg for Qbt 1g and Qbt 1v, and 1.9 mg/kg for Qbt 3. Background screening values for all rock units are well below the SAL of 380 mg/kg.

Total silver concentrations by INAA were below detection limits which ranged between 1 and 3 mg/kg.

Sodium (Na)

All of the 106 leachable sodium concentrations were above ICPES detection limits. Sodium concentrations for all geologic units range from 130 to 7700 mg/kg and average 1059 mg/kg.

Population characteristics from the Wilcoxon rank sum test (Table IV) resulted in pooling all of the sodium data for Qbt 1g and Qbt 1v (as data group Qbt 1). Qbt 2 and Qbt 3 were pooled as data group Qbt 23. Square root transformed sodium data are approximately normally distributed for data group Qbt 1. Log transformed sodium data are approximately normally distributed for data group Qbt 23. Box plots comparing acid leachable sodium by geologic unit show generally low concentrations for units Qbt 3, Qbt 4, and Tt relative to the other rock units (Fig.

4). Plots of leachable sodium from individual stratigraphic sections show that leachable sodium concentrations are greatest in the glassy tuffs (units Qbo, Qct, and Qbt 1g), and concentrations decrease up section in the overlying devitrified tuffs (Fig. 18).

The background screening values for leachable sodium are 610 mg/kg for Tt, 1900 mg/kg for Qbo, 3500 mg/kg for Qct, 4290 mg/kg for Qbt 1g and Qbt 1v, 1940 mg/kg for Qbt 2 and Qbt 3, and 390 mg/kg for Qbt 4.

Total sodium concentrations by XRF and INAA vary systematically as a function of stratigraphic position, but in sense opposite to that of the leachable sodium concentrations (Fig. 18). In the Tshirege Member, total sodium concentrations increase systematically up section through the tuff. Thus, tuffs that contain the lowest total sodium concentrations have the greatest concentrations of soluble sodium. At TA-49, total sodium concentrations tend to decrease up section in the upper part of the Qbo in the overlying tuffaceous sediments of Qct (Fig. 18).

Strontium (Sr)

Leachable strontium concentrations were not determined for this investigation because the total strontium results are consistently several orders of magnitude below the strontium SAL of 46000 mg/kg. Total strontium concentrations for the Bandelier Tuff range from below the detection limit of 5 mg/kg to 368 mg/kg and average 33 mg/kg.

In the Tshirege Member, total strontium concentrations increase slightly up section from Qbt 1g to Qbt 3 (Fig. 19). There is an abrupt increase in strontium concentrations above the Qbt 3/ Qbt 4 contact. Total strontium concentrations in the upper part of Qbo increase upsection and total strontium concentrations tend to be greater than in the overlying tuffs of Qct and Qbt 1g (Fig. 19). Strontium concentrations in the upper part of Qbo at TA-49 are notably greater than in the upper part of Qbo at TA-21 (Fig. 19). These differences probably reflect different patterns of Qbo deposition and erosion at the two sites. Based on its chemical characteristics, Qbo was probably either: 1) more deeply eroded at TA-21 than at TA-49 before being buried by the Tshirege Member or 2) stratigraphically higher Sr-rich tuffs were deposited at TA-49 but not at TA-21.

Sulfate (SO_4)

Sulfate concentrations were determined for rock samples on aliquots extracted in deionized water and analyzed by IC. All of the 106 leachable sulfate concentrations were above IC detection limits. Sulfate concentrations for all geologic units range from 1.5 to 815 mg/kg and average 56.9 mg/kg.

Population characteristics from the Wilcoxon rank sum test (Table IV) resulted in pooling the leachable sulfate data for Qbt 1g and Qbt 1v into one data group (Qbt 1) and then pooling the Qbt 1 data group with data for units Qbt 2 and Qbt 3 into a single data group (as Qbt 123). The

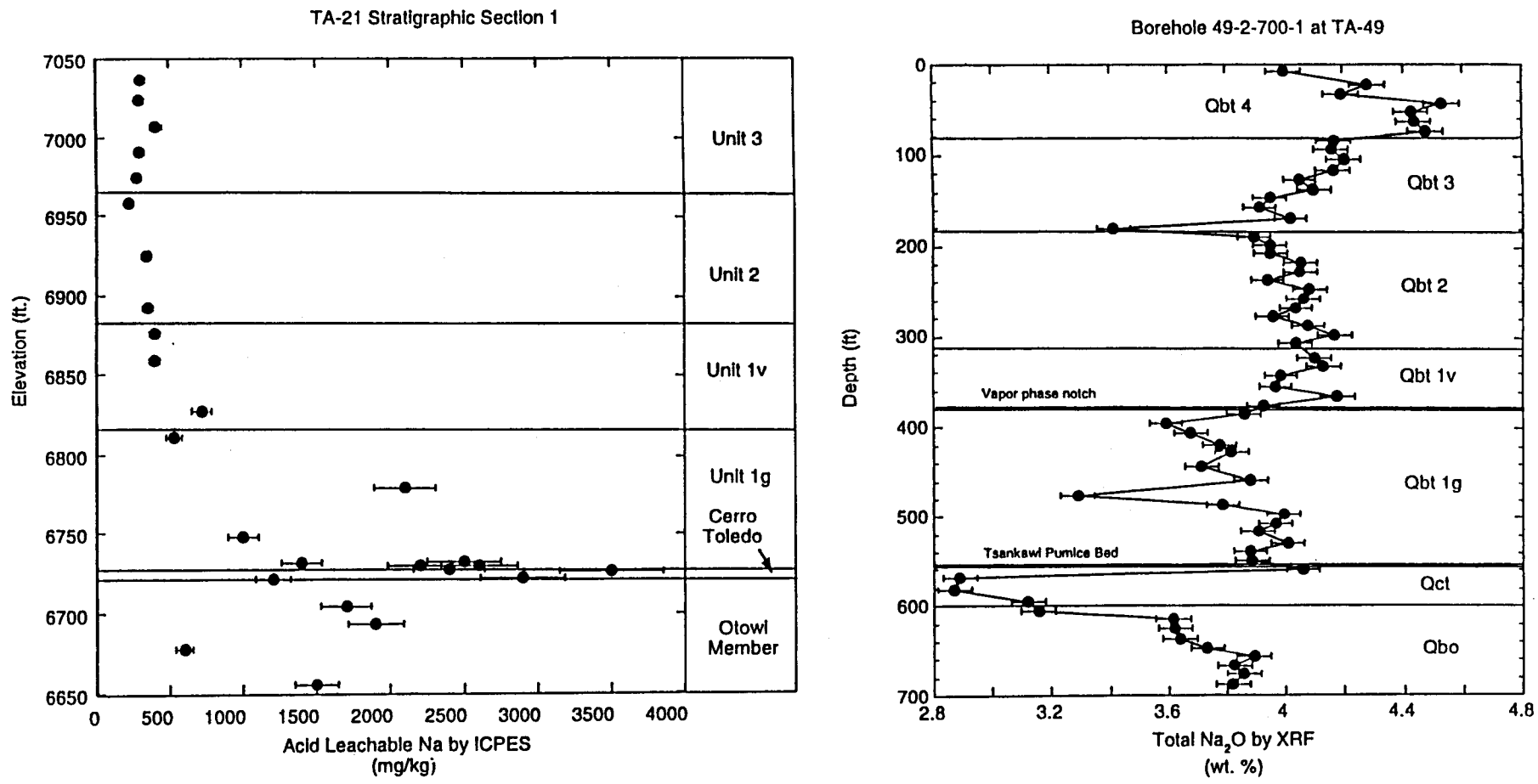


Fig. 18 PLOTS SHOWING EXAMPLES OF ACID LEACHABLE SODIUM CONCENTRATIONS AT TA-21 AND TOTAL SODIUM CONCENTRATIONS AT TA-49 AS A FUNCTION OF STRATIGRAPHIC HEIGHT IN THE BANDELIER TUFF.

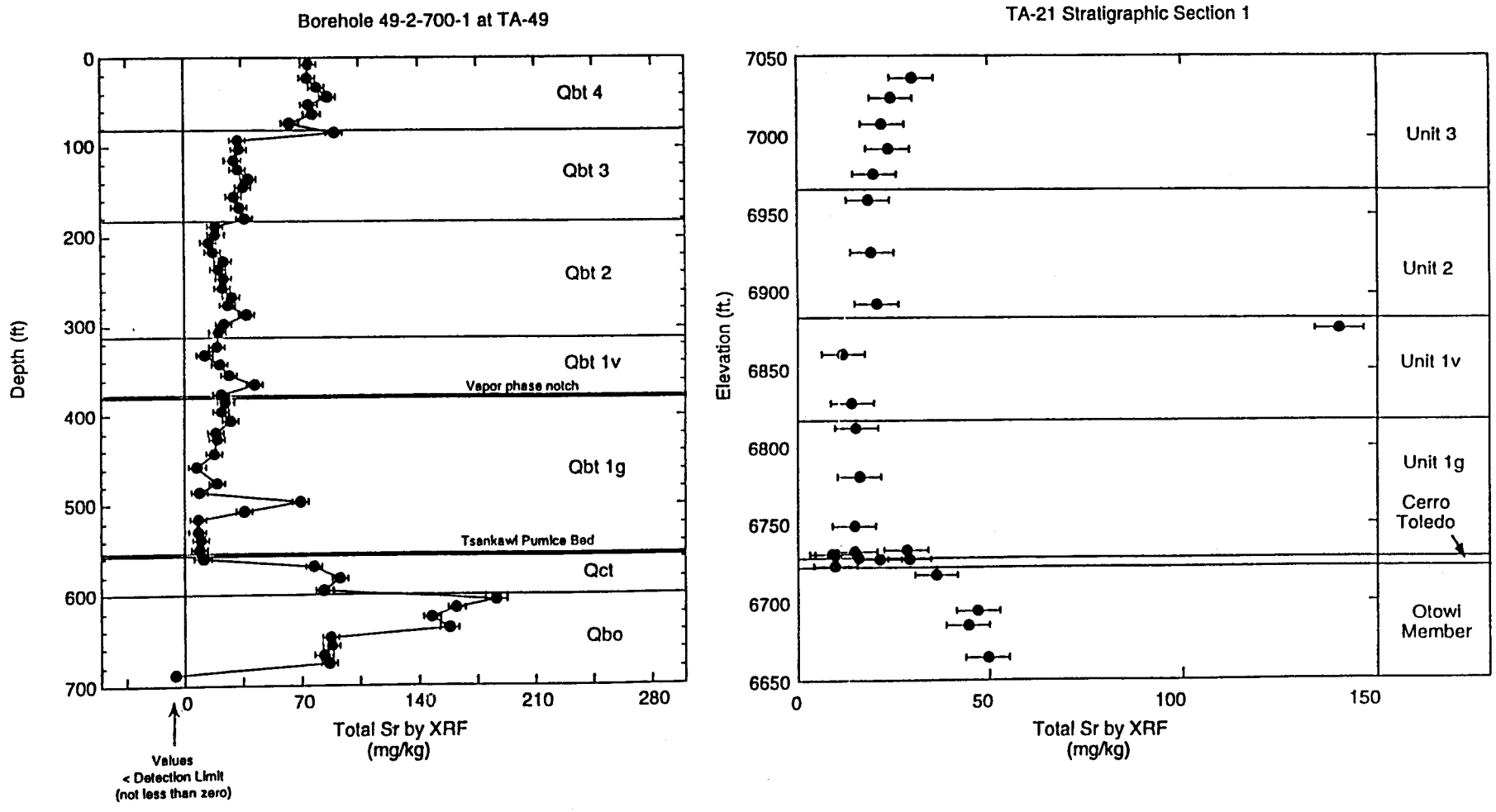


Fig. 19 PLOTS SHOWING TOTAL STRONTIUM CONCENTRATIONS AT TA-49 AND TA-21 AS A FUNCTION OF STRATIGRAPHIC HEIGHT IN THE BANDELIER TUFF.

resulting data group was bimodally distributed. Box plots comparing leachable sulfate by geologic unit show that medians, arithmetic means, and middle 50 percent ranges are generally greater for units Qct and Qbt 1g than for the other units (Fig. 4).

The greatest concentrations of sulfate are associated with the contact between the lower Tshirege Member (including the Tsankawi Pumice Bed) and the tephras and volcaniclastic sediments of the Cerro Toledo interval (Fig. 20). Soluble chlorine concentrations are also elevated in this interval. The presence of elevated concentrations of water soluble species such as sulfate and chlorine in these tuffs suggest that they have acted as preferential ground water pathways at some point after their deposition. These tuffs are now well above the canyon floor, and there is no evidence of perching of present-day ground water in these units. It is possible that these units were preferential ground water pathways when Los Alamos Canyon was shallower, and these units were below the level of perched alluvial ground water bodies on the canyon floor. Elevated sulfate also occurs at the Qbt 2/Qbt 3 contact at TA-67 (Fig. 20).

Instead of estimating a mixture distribution because of the bimodality in each data group, we use the maximum leachable sulfate concentration for each data group for the background screening values. The background screening values are 38.6 mg/kg for Tt, 12.7 mg/kg for Qbo, 548 mg/kg for Qct, 26.4 mg/kg for Qbt 4, and 815 mg/kg for Qbt 1g, Qbt 1v, Qbt 2, and Qbt 3.

Tantalum (Ta)

Twenty-one of the 106 leachable tantalum concentrations were above ICPMS detection limits. No statistical distribution of the tantalum was estimated because of the small sample population. For samples above detection limits, tantalum concentrations for all geologic units range from 0.2 to 2 mg/kg and average 0.43 mg/kg.

Box plots comparing acid leachable tantalum by geologic unit show concentrations above detection limits occur most often in Qbo and Qbt 4 relative to the other rock units (Fig. 4). Plots of leachable tantalum from individual stratigraphic sections showed no clear relation between above detection limit tantalum concentrations and stratigraphic height. In two cases, above detection limit leachable tantalum concentrations are associated with crystal-rich surge deposits at unit contacts (Fig. 21).

The background screening values for leachable tantalum are based on maximum detected concentrations in each rock unit. Background screening values are 0.2 mg/kg for Tt, 0.9 mg/kg for Qbo, 0.3 mg/kg for Qct, 0.3 mg/kg for Qbt 1g, 0.5 mg/kg for Qbt 1v, 2 mg/kg for Qbt 2, 0.8 mg/kg for Qbt 3, and 0.5 mg/kg for Qbt 4.

Total tantalum concentrations by INAA decrease systematically up section in the Tshirege Member (Fig. 21). Total tantalum in the upper Tshirege Member is about one-third of that in the lower part. Tantalum concentrations in the upper Otowi Member are about half of those found in the lower Tshirege Member.

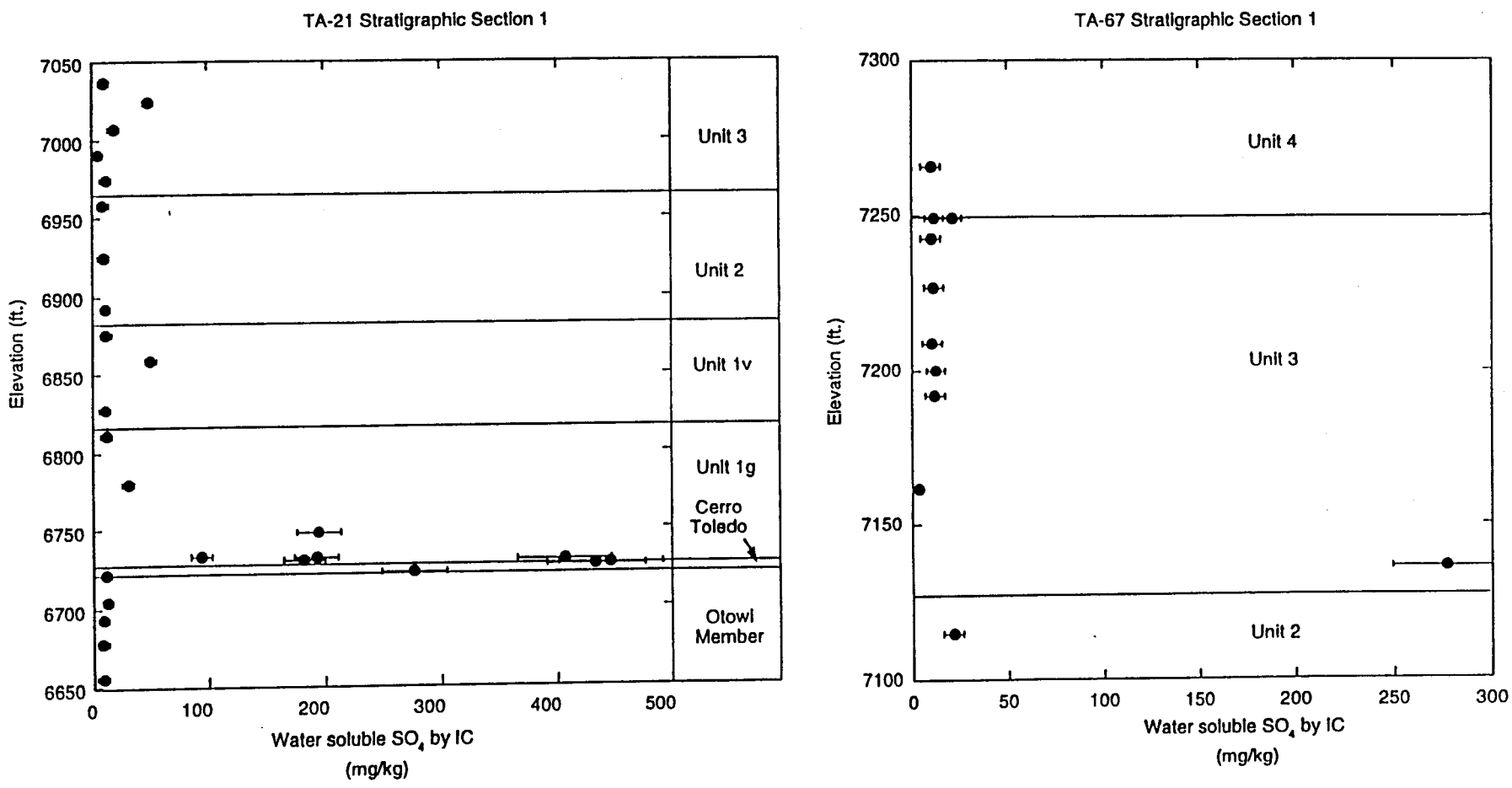


Fig. 20 Plots showing examples of water soluble sulfate concentrations at TA-21 and at TA-67 as a function of stratigraphic height in the Bandelier Tuff.

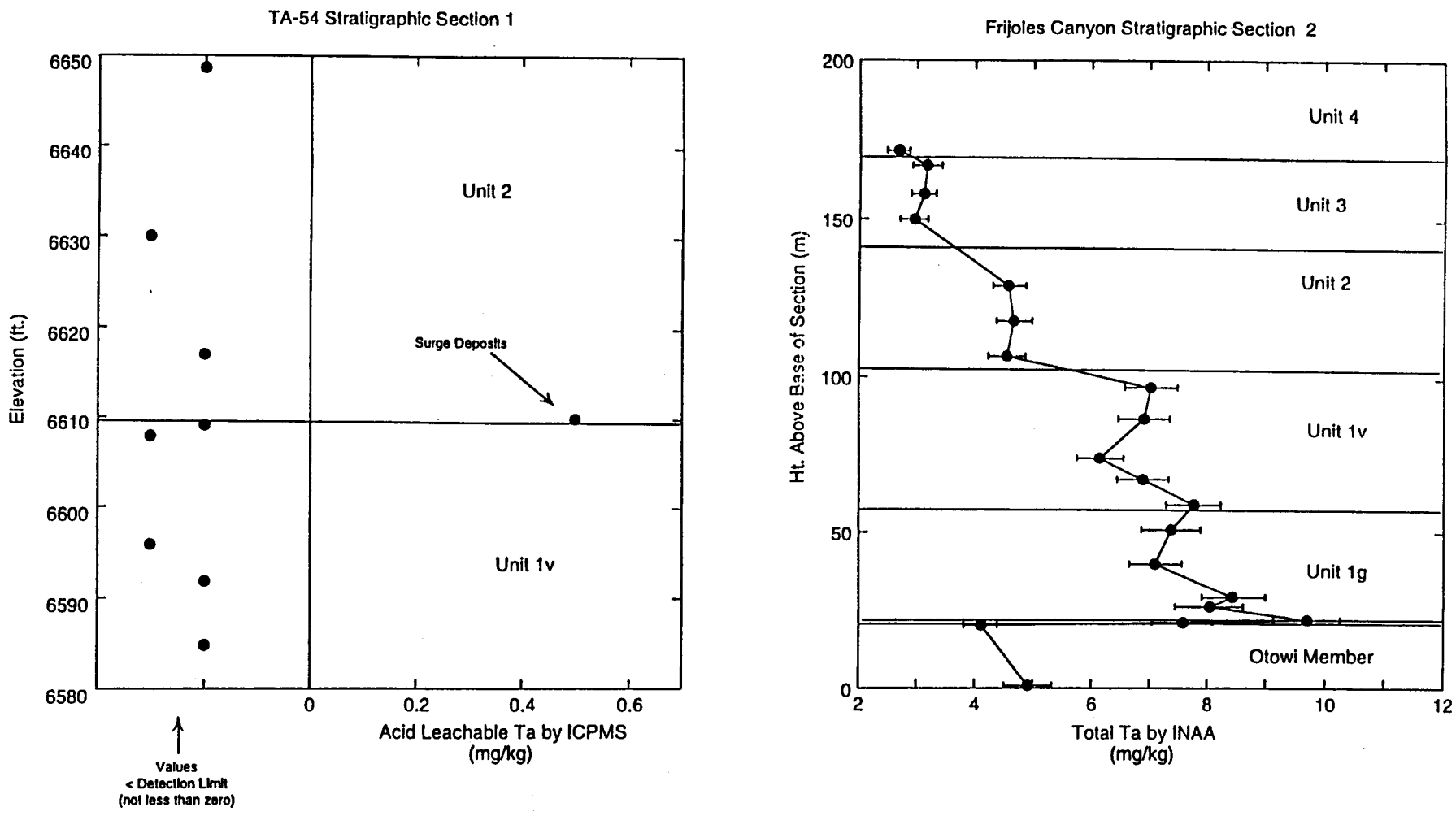


Fig. 21 PLOTS SHOWING EXAMPLES OF ACID LEACHABLE TANTALUM CONCENTRATIONS AT TA-54 AND TOTAL TANTALUM CONCENTRATIONS AT FRIJOLES CANYON AS A FUNCTION OF STRATIGRAPHIC HEIGHT IN THE BANDELIER TUFF.

Thallium (Tl)

Twenty-four of the 106 leachable thallium concentrations were above ICPMS detection limits. No statistical distribution of the thallium was estimated because of the small sample population. For samples above detection limits, thallium concentrations for all geologic units range from 0.2 to 1.7 mg/kg and average 0.73 mg/kg.

Box plots comparing acid leachable thallium by geologic unit generally show concentrations above detect limits occur most often in Qbo and Qbt 1g relative to the other rock units (Fig. 4). Plots of leachable thallium from individual stratigraphic sections show that above detection limit thallium concentrations are associated with the Qbt 1g/Qbt 1v contact or with tuffs near the base of Qbt 1g and in the upper part of Qbo (Fig. 22).

The background screening values for leachable thallium are based on maximum detected concentrations in each rock unit. Background screening values are <0.3 mg/kg for Tt, 0.9 mg/kg for Qbo, <0.2 mg/kg for Qct, 0.7 mg/kg for Qbt 1g, 1.7 mg/kg for Qbt 1v, 1.3 mg/kg for Qbt 2, 1.7 mg/kg for Qbt 3, and <0.3 mg/kg for Qbt 4. The background screening values are less than the thallium SAL of 5.4 mg/kg.

Thorium (Th)

All of the 106 leachable thorium concentrations were above ICPMS detection limits. Square root transformed thorium data are approximately normally distributed. Thorium concentrations for all geologic units range from 0.5 to 22 mg/kg and average 6.31 mg/kg.

Population characteristics from the Wilcoxon rank sum test (Table IV) resulted in pooling the thorium data for Qbt 1g, Qbt 1v, Qbt 2 and Qbt 3 as four separate data groups. Box plots comparing acid leachable thorium by geologic unit show generally high concentrations for units Qbt 1v and Qbt 2 and low concentrations for units Qbo, Qbt 1g, Qct, and Tt relative to the other rock units (Fig. 4). Plots of leachable thorium from individual stratigraphic sections show that leachable thorium concentrations typically are low in the glassy tuffs in Qbo and in the basal part of the Tshirege Member (Fig. 23). However, leachable thorium concentrations abruptly increase by about an order of magnitude in the crystalline tuffs above the Qbt 1g/Qbt 1v contact. Above this contact, thorium concentrations decrease up section (Fig. 23).

The background screening values for leachable thorium are 6.4 mg/kg for Tt, 1.4 mg/kg for Qbo, 4.2 mg/kg for Qct, 7.69 mg/kg for Qbt 1g, 22.1 mg/kg for Qbt 1v, 11.5 mg/kg for Qbt 2, 9.29 mg/kg for Qbt 3, and 6.1 mg/kg for Qbt 4.

Total thorium concentrations by INAA decrease systematically up section from the base of the Tshirege Member (Fig. 23). Total thorium in the upper Tshirege Member is about one-third of that in the lower part. Thorium concentrations in the upper Otowi Member are about half of that found in the lower Tshirege Member. Comparison of acid leachable and total thorium data shows that approximately 10% to 40% of the thorium in the Bandelier Tuff is susceptible to leaching by nitric acid at a pH of 1.

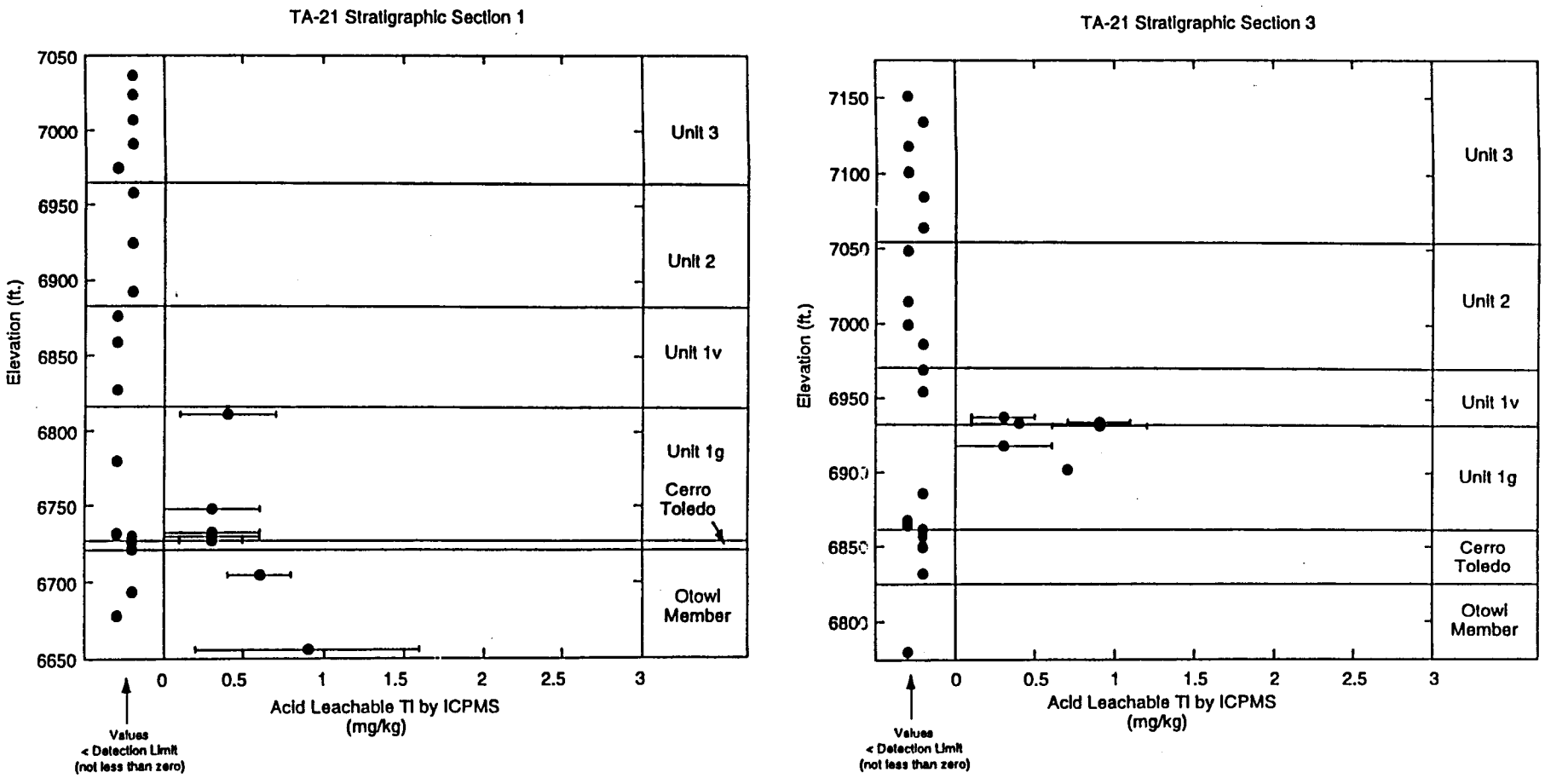


Fig. 22 PLOTS SHOWING EXAMPLES OF ACID LEACHABLE THALLIUM CONCENTRATIONS AT TA-21 AS A FUNCTION OF STRATIGRAPHIC HEIGHT IN THE BANDELIER TUFF.

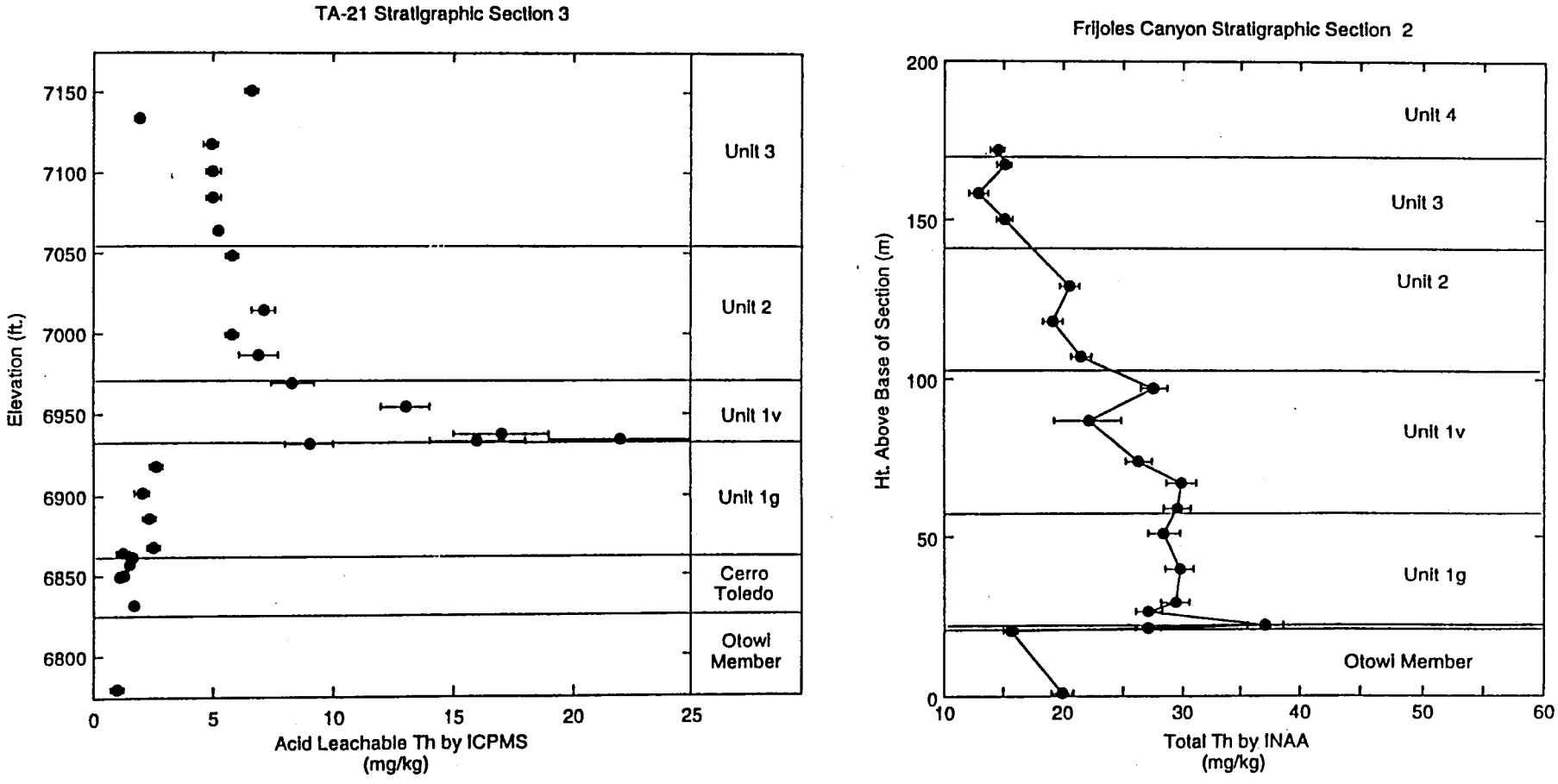


Fig. 23 PLOTS SHOWING EXAMPLES OF ACID LEACHABLE THORIUM CONCENTRATIONS AT TA-21 AND TOTAL THORIUM CONCENTRATIONS AT FRIJOLES CANYON AS A FUNCTION OF STRATIGRAPHIC HEIGHT IN THE BANDELIER TUFF.

Uranium (U)

Ninety-two of the 106 leachable uranium concentrations were above ICPMS detection limits. Square root transformed uranium data are approximately normally distributed. Uranium concentrations for all geologic units range from 0.2 to 5.7 mg/kg and average 1.28 mg/kg.

Population characteristics from the Wilcoxon rank sum test (Table IV) resulted in pooling the uranium data for Qbt 1g, Qbt 1v, Qbt 2 and Qbt 3 as four separate data groups. Box plots comparing acid leachable uranium by geologic unit show generally high concentrations for unit Qbt 1v and low concentrations for units Qbo, Qbt 1g, Qct, and Tt relative to the other rock units (Fig. 4). Plots of leachable uranium from individual stratigraphic sections show that leachable uranium concentrations typically are low in the glassy tuffs in Qbo and in the basal part of the Tshirege Member, and they abruptly increase above the Qbt 1g/Qbt 1v contact (Fig. 24). Above this contact, uranium concentrations decrease up section.

The background screening values for leachable uranium are 0.6 mg/kg for Tt, 0.2 mg/kg for Qbo, 0.4 mg/kg for Qct, 1.39 mg/kg for Qbt 1g, 5.93 mg/kg for Qbt 1v, 2.48 mg/kg for Qbt 2, 1.64 mg/kg for Qbt 3, and 0.9 mg/kg for Qbt 4. Background screening values for uranium in all rock units are well below the SAL of 95 mg/kg.

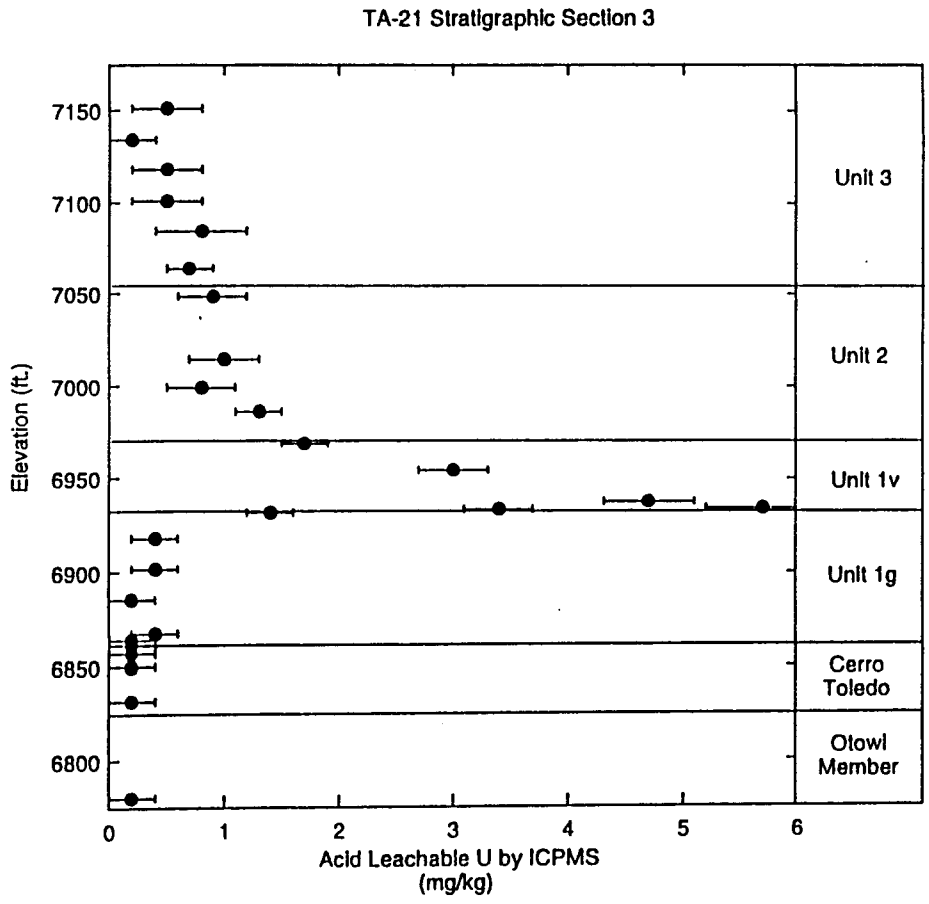
Total uranium concentrations by INAA decrease systematically up section from the base of the Tshirege Member (Fig. 24). Total uranium in the upper Tshirege Member is about one-half of that in the lower part. Uranium concentrations in the upper Otowi Member are about 25% less than those found in the lower Tshirege Member. Comparison of acid leachable and total uranium data shows that between 5% and 50% of the total uranium in the Bandelier Tuff is susceptible to leaching by nitric acid at a pH of 1.

Vanadium (V)

Ninety of the 106 leachable vanadium concentrations were above ICPES detection limits of 0.4 to 1.4 mg/kg. The vanadium data are approximately normally distributed. Vanadium concentrations for all geologic units range from 0.8 to 29 mg/kg and average 3.08 mg/kg.

Population characteristics from the Wilcoxon rank sum test (Table IV) resulted in pooling the vanadium data for Qbt 1g as a separate data group and Qbt 1v, Qbt 2, and Qbt 3 as another data group (Qbt1v,2,3). Box plots comparing acid leachable aluminum by geologic unit show that medians, arithmetic means, and middle 50 percent ranges are distinctly greater for units Tt and Qbt 4 than for the other units (Fig. 4). Plots of leachable vanadium from individual stratigraphic sections show that leachable vanadium concentrations are relatively constant in units Qct 1g through Qbt 3 of the Tshirege Member (Fig. 25). Soluble vanadium concentrations in Qbt 4 are approximately four times greater than those in the underlying tuffs of the Tshirege Member.

The background screening values for leachable vanadium are 29 mg/kg for Tt, 2.8 mg/kg for Qbo, 3.8 mg/kg for Qct, 1.67 mg/kg for Qbt 1g, 9.5 mg/kg for Qbt 4, and 4.01 mg/kg for Qbt 1v, Qbt 2, and Qbt 3. Background screening values for vanadium in all rock units are well below the SAL of 540 mg/kg.



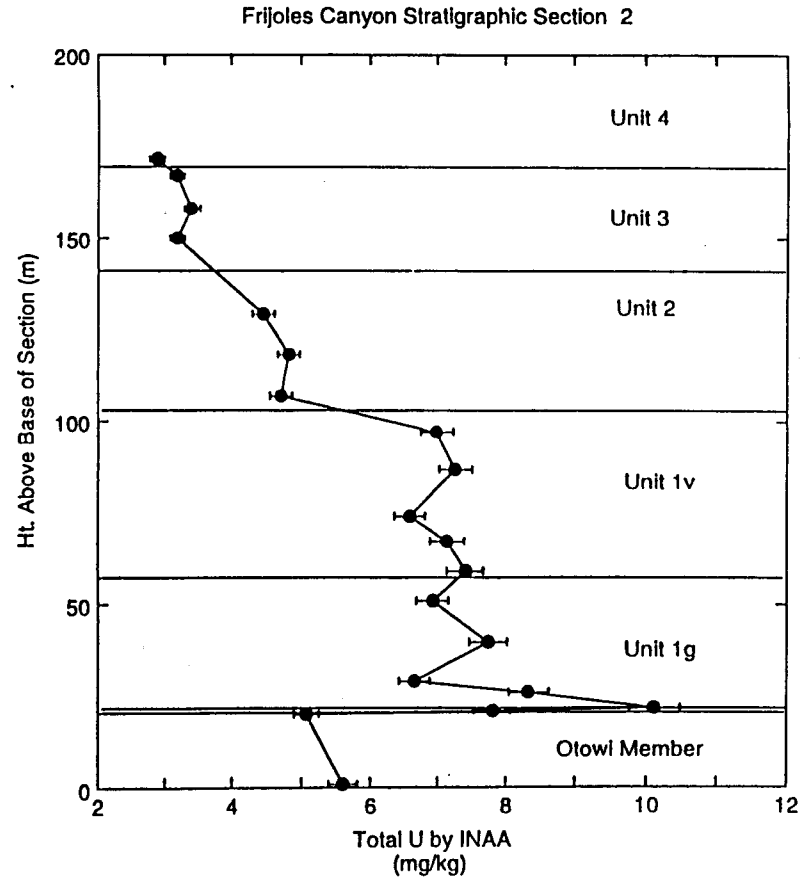


Fig. 24 PLOTS SHOWING EXAMPLES OF ACID LEACHABLE URANIUM CONCENTRATIONS AT TA-21 AND TOTAL URANIUM CONCENTRATIONS AT FRIJOLES CANYON AS A FUNCTION OF STRATIGRAPHIC HEIGHT IN THE BANDELIER TUFF.

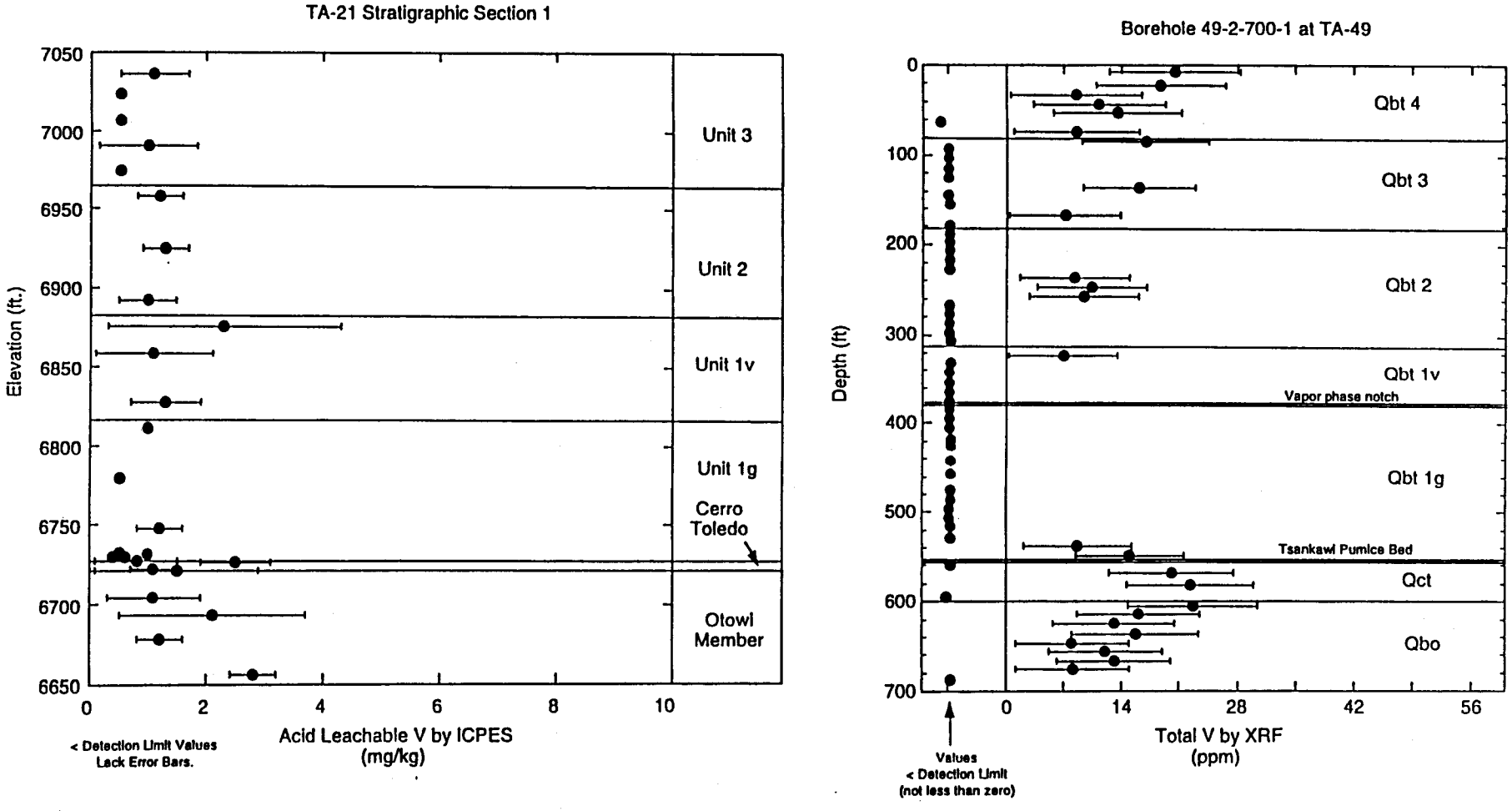


Fig. 25 PLOTS SHOWING EXAMPLES OF ACID LEACHABLE VANADIUM CONCENTRATIONS AT TA-21 AND TOTAL VANADIUM CONCENTRATIONS AT TA-49 AS A FUNCTION OF STRATIGRAPHIC HEIGHT IN THE BANDELIER TUFF.

About 40% of total vanadium concentrations by XRF are above the detection limit of approximately 7 mg/kg (Fig. 25). Total vanadium concentrations in the vitric tuffs at the base of the Tshirege Member (Qbt 1g) were generally below the detection limit whereas about half of the vanadium concentrations in overlying tuffs were above the detection limit, with the greatest concentrations occurring in Qbt 4 (Fig. 25). Total vanadium concentrations in Qbo are similar to those in upper part of the Tshirege Member.

Zinc (Zn)

All of the 106 leachable zinc concentrations were above ICPES detection limits. Zinc concentrations for all geologic units range from 5.3 to 84 mg/kg and average 32.1 mg/kg.

Population characteristics from the Wilcoxon rank sum test (Table IV) resulted in pooling the zinc data for Qbt 1g, Qbt 2 and Qbt 3 as data group Qbt 1g23; Qbt 1v was treated as a separate data group. Box plots comparing acid leachable zinc by geologic unit show generally high concentrations for unit Qbt 1v and low concentrations for units Qbo and Qct relative to the other rock units (Fig. 4). Plots of leachable zinc from individual stratigraphic sections show that leachable zinc concentrations typically are low in the glassy tuffs Qbo and in the basal part of Qbt 1g (Fig. 26). Leachable zinc increases up section in Qbt 1g, reaching a maximum at the Qbt 1g/Qbt 1v contact (at the vapor phase notch). Above this contact, zinc concentrations decrease up section.

The background screening values for leachable zinc are 41 mg/kg for Tt, 21 mg/kg for Qbo, 17 mg/kg for Qct, 84.6 mg/kg for Qbt 1v, 47 mg/kg for Qbt 4, and 55.5 mg/kg for Qbt 1g, Qbt 2, and Qbt 3. Background screening values for zinc in all rock units are well below the SAL of 23000 mg/kg.

Total zinc concentrations by XRF decrease slightly up section from Qbt 1g to the middle of Qbt 3 (Fig. 26). Zinc concentrations abruptly increase in the middle of Qbt 3 and remain relatively constant up section into Qbt 4. Total zinc concentrations tend to increase up section in the upper part of the Qbo, and the top of Qbo is generally depleted in zinc relative to the lower part of Qbt 1g. The percentage of total zinc susceptible to acid leaching in the Bandelier Tuff varies with stratigraphic position. Approximately 50% to 80% of the zinc in upper Qbt 1g and in Qbt 1v is released by leaching in a solution of nitric acid at a pH of 1. However, only 10% to 20% of the zinc in other parts of the Bandelier Tuff is dissolved by the nitric acid solution.

Radionuclide Background Screening Values

Background screening values for activities of naturally occurring potassium, thorium, and uranium isotopes were calculated using total elemental concentrations and assuming secular isotopic equilibrium in the tuffs. Isotopic screening activities were calculated by multiplying the total element background screening value by the percent natural abundance of the iso-

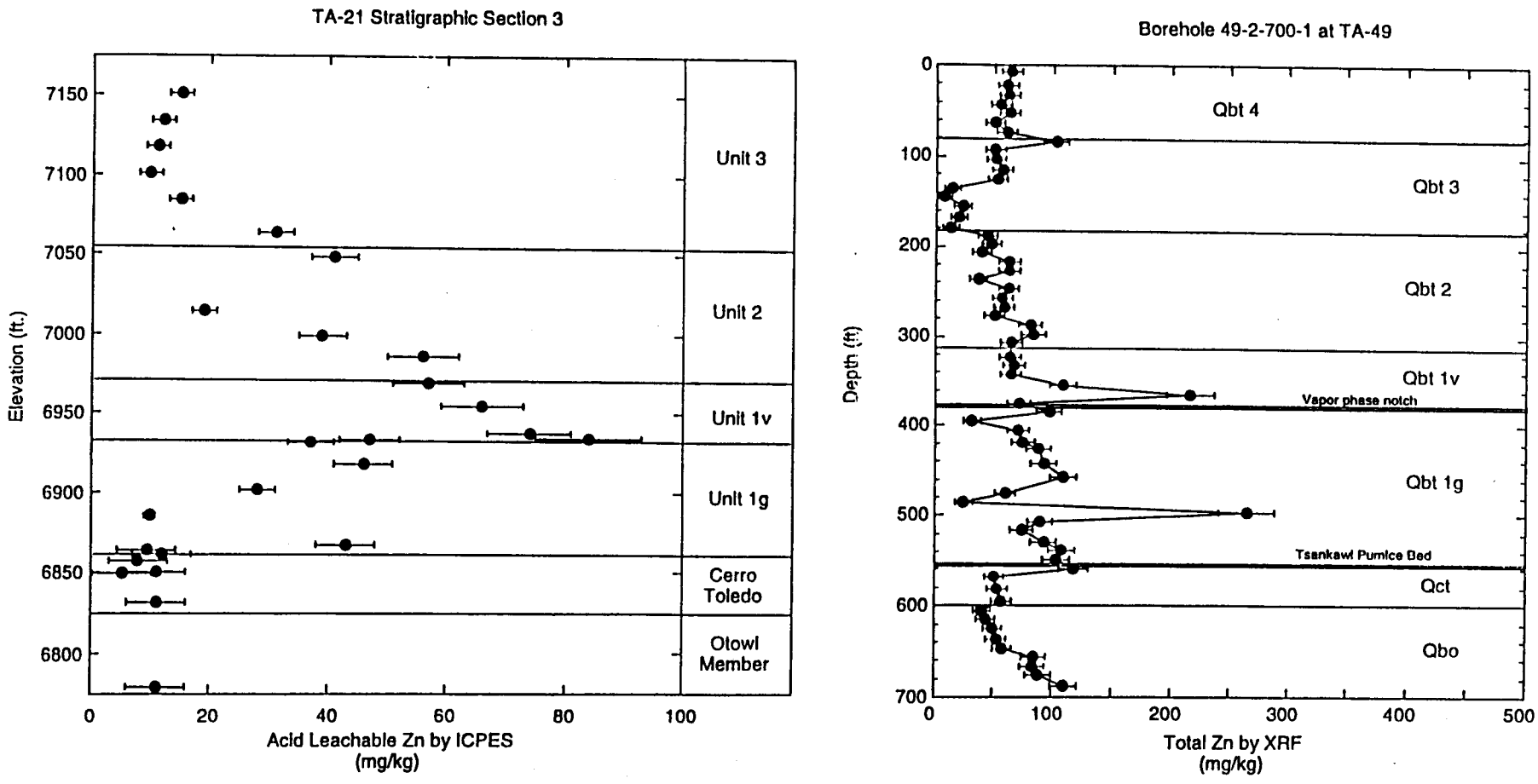


Fig. 26 PLOTS SHOWING EXAMPLES OF ACID LEACHABLE ZINC CONCENTRATIONS AT TA-21 AND TOTAL ZINC CONCENTRATIONS AT TA-49 AS A FUNCTION OF STRATIGRAPHIC HEIGHT IN THE BANDELIER TUFF.

tope of interest and the specific activity of that isotope. Radium-226 activities were measured for a limited suite of samples, and background screening values for this isotope are also discussed.

The radionuclide background screening activities were calculated using INAA data for 47 samples of Bandelier Tuff collected at two sections in Frijoles Canyon. A summary of background screening activities for radionuclides is presented in Table VIII.

Potassium-40

All of the total potassium concentrations were above INAA detection limits. Potassium concentrations for all geologic units range from 28760 to 47920 mg/kg and average 38137 mg/kg. The potassium data are approximately normally distributed. Population characteristics from the Wilcoxon rank sum test resulted in pooling all of the potassium data for Qbt 1g, Qbt 1v, Qbt 2, and Qbt 3 (as data group Qbt 123). Qbt 4 was pooled as a separate data group.

The background screening activities for potassium-40 are 30.4 pCi/g for Qbo, 36.9 pCi/g for Qbt 1g, Qbt 1v, Qbt 2, and Qbt 3, and 37.0 pCi/g for Qbt 4 (Table VIII).

Radium (Ra)

Thirteen Bandelier Tuff samples were analyzed for Radium-226 activities by gamma-ray spectroscopy. No statistical distribution of the radium-226 was estimated because of the small sample population. Radium activities range from 1.72 to 7.15 pCi/g and average 4.92 in the 13 samples analyzed.

Box plots comparing radium-226 activities by geologic unit show that radium-226 activities tend to decrease up section, with the highest activities occurring in unit Qbo and the lowest in Qbt 3 (Fig. 4). Radium-226 activities increase in Qbo 4 relative to the underlying tuffs. Radium-226 activities were not determined for units Qct and Tt.

The background screening values for radium-226 are based on maximum activities in each rock unit. Background screening values are 7.15 pCi/g for Qbo, 6.78 pCi/g for Qbt 1g, 6.61 pCi/g for Qbt 1v, 4.82 pCi/g for Qbt 2, 2.6 pCi/g for Qbt 3, and 6.23 pCi/g for Qbt 4. Six of the thirteen tuff samples analyzed in this study have ^{226}Ra activities that exceed the SAL of 5 pCi/g.

Thorium-232

All of the total thorium concentrations were above INAA detection limits. Thorium concentrations for all geologic units range from 12.7 to 37.1 mg/kg and average 22.7 mg/kg. Statistical distributions for total thorium were not evaluated because of the small sample size for each stratigraphic unit. Maximum concentrations are used to calculate background screening activities for all units.

TABLE VIII.

COMPUTED BACKGROUND SCREENING VALUES FOR NATURALLY OCCURRING RADIONUCLIDES COMPILED BY GEOLOGICAL UNITS

Analyte[1]	Qbo	Qbt 1g	Qbt 1v	Qbt 2	Qbt 3	Qbt 4	SAL
Total Potassium (mg/kg)	*37200*	*45100*	*45100*	*45100*	*45100*	*45300*	NA
Potassium-40 (pCi/g)	30.4	36.9	36.9	36.9	36.9	37.0	NA
Radium-226 (pCi/g measured)	7.15	6.78	6.61	4.82	2.6	6.23	5
Total Thorium (mg/kg)	*19.9*	*37.1*	*30.1*	*25.9*	*16.3*	*15.6*	NA
Thorium-232 (pCi/g)	2.17	4.05	3.29	2.83	1.78	1.70	5
Total Uranium (mg/kg)	*5.61*	*10.1*	*7.59*	*7.12*	*4.37*	*2.93*	95
Uranium-234 (pCi/g)	1.99	3.59	2.70	2.53	1.55	1.04	86
Uranium-235 (pCi/g)	0.086	0.155	0.116	0.109	0.067	0.045	18
Uranium-238 (pCi/g)	1.87	3.37	2.53	2.37	1.46	0.98	59
Total Uranium (pCi/g)	3.95	7.12	5.34	5.01	3.08	2.06	66

NA - Not available.

The background screening activities for thorium-232 are 2.17 pCi/g for Qbo, 4.05 pCi/g for Qbt 1g, 3.29 pCi/g for Qbt 1v, 2.83 pCi/g for Qbt 2,1.78 pCi/g for Qbt 3, and 1.70 pCi/g for Qbt 4 (Table VIII). The background screening activities for thorium-232 are below the SAL of 5 pCi/g.

Uranium Isotopes

All of the total uranium concentrations were above INAA detection limits. Uranium concentrations for all geologic units range from 2.8 to 10.1 mg/kg and average 5.89 mg/kg. Statistical distributions for total uranium were not evaluated because of the small sample size for each stratigraphic unit. Maximum concentrations are used to calculate background screening activities for all units. Uranium background screening activities are summarized by isotope in Table VIII. The background screening activities for uranium isotopes are below SALs.

Use of Bivariate Plots in Background Comparisons

In addition to their use in deriving background screening values, the background data in this report also can be used to define natural geochemical trends in rock units. These trends provide another tool for evaluating whether elemental concentrations determined during an RFI are naturally occurring or if their geochemical signature is outside the normal range found in the bedrock units. The background element pairs of uranium vs. thorium, lead vs. zinc, and zinc vs. thorium show the greatest degree of correlation for the leachable inorganic elements (Fig. 27).

The leachable uranium and thorium concentrations are the most strongly correlated elements in the data set, and they are the best element pair for defining the natural geochemistry of the Bandelier Tuff. Samples with leachable elemental concentrations significantly outside the uranium and thorium data trend should be considered as potentially contaminated and evaluated further. The lead vs. zinc and zinc vs. thorium regression curves are not correlated as well, but they still may be useful in identifying obvious data outliers (Fig. 27).

Data evaluations must be done with caution because some outliers to the main data trends may be naturally occurring. Naturally occurring outliers can be present where primary magmatic trends are overprinted by secondary alteration. The potassium vs. sodium plot (Fig. 27) provides a good example where two naturally occurring geochemical trends are defined by the data set. Most samples fall along the lower linear regression line and probably represent the leachable compositions of the tuff soon after emplacement. The upper linear regression curve represents glassy tuffs from stratigraphic section 1 at TA-21. Glassy tuffs are susceptible to diagenetic alteration, and as the chlorine and sulfate data discussed above show, the tuffs at this location were probably altered by ground water sometime after their deposition.

CONCLUSIONS AND RECOMMENDATIONS

Background elemental concentrations were determined for inorganic constituents of the Bandelier Tuff and for some older rock units as baseline data for RCRA facilities investigations. These data meet the requirements for characterizing the chemistry of uncontaminated rock units for use in comparisons to identify areas of contamination, perform baseline risk assessments, and plan remedial actions. These data supplement information from earlier background soil and tuff investigations by Longmire et al. (1994a) and the companion report to this study (Longmire et al., 1995b).

Two types of analytical data for inorganic constituents are presented. Leachable elemental concentrations provide information about the bioavailabilty of elements for risk assessment calculations. The leachable elemental concentrations are treated statistically and are the primary focus of this investigation. Total elemental concentrations are used for calculating background screening values for naturally occurring potassium, thorium, and uranium isotopes, and they provide supporting data for understanding the distribution of inorganic elements in the rock units.

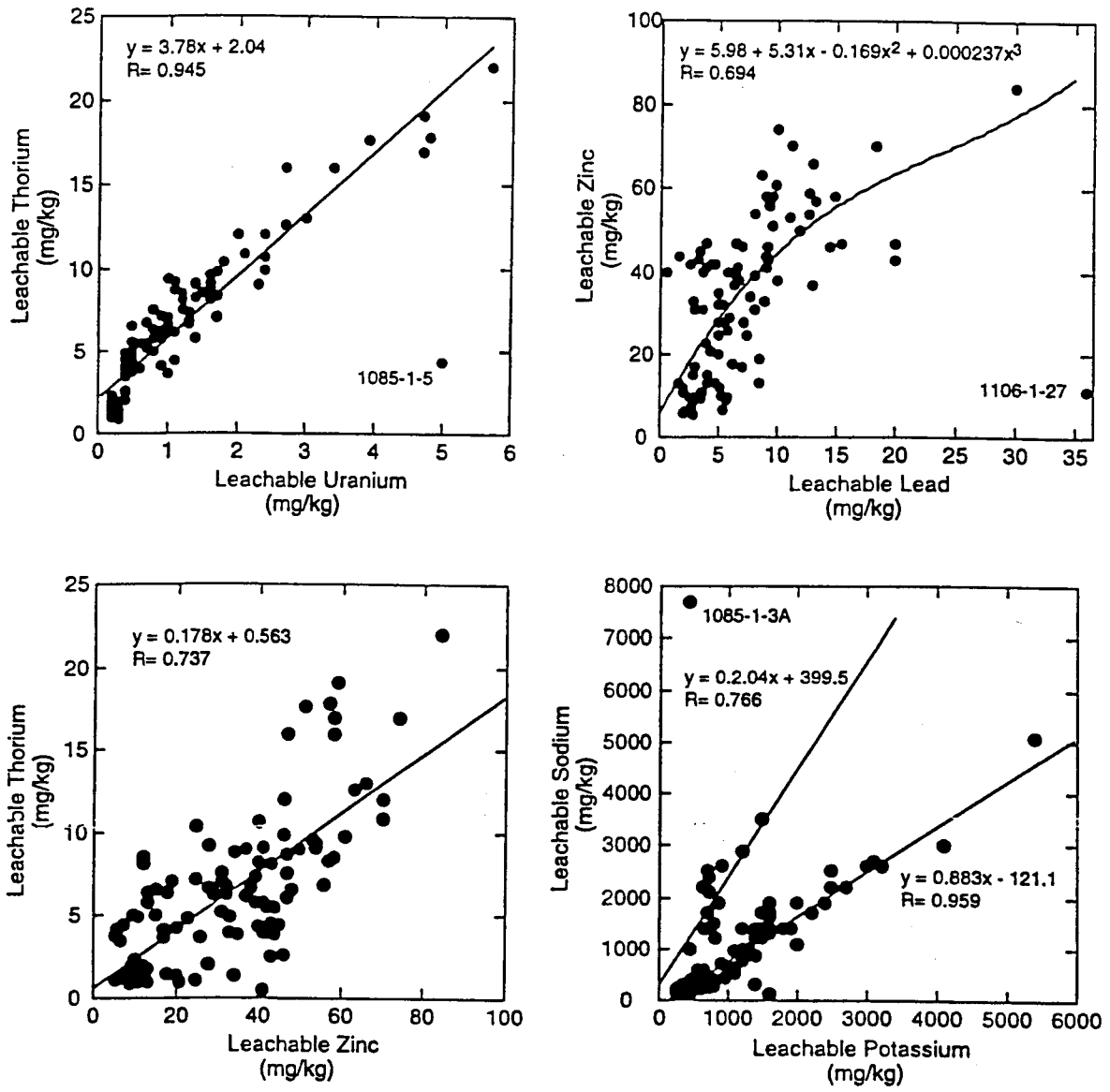


Fig. 27 Bivariant plots showing natural elemental distribution for leachable analytes in the Bandelier Tuff. Outliers, which are labeled with their sample numbers, were not used to calculate regression curves. The background data can be used to define natural geochemical trends in rock units as shown in the uranium vs. thorium, lead vs. zinc, and zinc vs. thorium plots. Such plots should be interpreted with caution because some outliers to the main data trends may be naturally occurring. The potassium vs. sodium plot provides a good example where two naturally occurring geochemical trends are defined by the data set. The samples falling along the lower linear regression line probably represent the leachable compositions of the tuff soon after emplacement whereas the upper linear regression curve represents glassy tuffs that were probably altered by ground water sometime after their deposition.

The field, analytical, and statistical methods used in this investigation are sufficient for defining background element concentrations for inorganic contaminants of concern. The spatial coverage and population size of background chemistry samples are adequate for defining background screening values for units Qbt 1g, Qbt 1v, Qbt 2, and Qbt 3 of the Tshirege

Member. These tuffs are the most widespread rock units on the Pajarito Plateau and make up the bedrock at the majority of the Laboratory's potential release sites. No additional background data are needed for these units.

We recommend additional background characterization of Qbt 4 because so few samples of this unit are included in the present data set. Qbt 4 is an important geologic unit because it has unique geochemical characteristics compared to other parts of the Tshirege Member and because it is the surface bedrock unit underlying potential release sites in the western part of the Laboratory. The need for additional Qbt 4 background data will be mitigated in part by ongoing local background investigations being done in support of clean closure of MDA P at TA-16. We recommend that characterization of Qbt 4 be completed by analyzing samples from the background geology borehole 49-2-700-1 at TA-49 which penetrated 25 m of Qbt 4 at the top of the section.

Additional background data are presented for some of the pre-Tshirege rock units including, in descending stratigraphic order: tephras and volcaniclastic sediments of the Cerro Toledo interval, the upper part of the Otowi Member of the Bandelier Tuff, and dacitic lavas of the Tschicoma Formation. These background data provide useful bounding information on the geochemistry of these deeper units, but they are considered preliminary because so few samples of these units are included in the present data set. Because these rock units directly underlie so few potential release sites, we recommend that local background data be collected for these units on an as needed basis.

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APPENDIX I

S-PLUS CODE USED TO CALCULATE LOGNORMAL UTLS

File: lnorm_utl1.s

```
function(q,p,n,ave,sd,nt)
{
# lnorm_utl1.s is used as function LUTL1 in Splus
# This function is used to estimate the upper 95% CI of the 95th
# percentile for a lognormal distribution.  Uses Gilbert's MBE of LN.
#    q = the quantile to estimate
#    p = the confidence limit of q
#    n = number of values sampled
#  ave = mean of logtranformed data
#   sd = st. dev. of logtranformed data
#   nt = number of simulation trials
#.............................................................

# Calculate the qth quantile of the normal distribution
q1_qnorm(q)

# Initialize arrays
t1_rep(-1,n)
t2_rep(-1,nt)

i_0

repeat

 { i_i+1

# Get the "n" lognormal samples
   t1_rlnorm(n,ave,sd)

# Calculate the mean and sd the "Gilbert" way
   dummy_lnormUMV.s(t1)
   ave1_dummy$mu
   sd1_sqrt(dummy$s2)

# Calculate an estimate of the 95th percentile
   t2[i]_exp(ave1+q1*sd1)
   if(i>=nt) break
 }
```

```
# Find the upper p*100% of the qth percentile
quantile(t2,p)
}
```

File: lnormUMV.s

```
function(x)
{
# lnormUMV.s (Splus function)
# Calls: psi.s
# Min Variance Unbiased ests of parameters of lognormal(mu,var=s2) distn
# for X~lognorm(mu,s2), Y=log(X)~normal(mu,s2)
# returns:E=mean(X), V=var(X)
#       mu=mean(Y),s2=var(Y)
# ref:Gilbert('87),Stat Methods for Env Pollution Mon, pp165-166
        n <- length(x)
        y <- log(x)
        ymu <- mean(y)
        vy <- var(y)
        psi1 <- psi.s(vy/2, n)
        psi2 <- psi.s(2 * vy, n)
        psi3 <- psi.s((vy * (n - 2))/(n - 1), n)
        E <- exp(ymu) * psi1
        V <- exp(2 * ymu) * (psi2 - psi3)
        mu <- log(E^2/(V + E^2)^0.5)
        s2 <- log(V/E^2 + 1)
        return(E, V, mu, s2)
}
```

File: psi.s

```
function(t, n)
{
# psi.s (Splus function)
# called by lnormUMV.s
# psi function in Gilbert('87) Stat. Meth. Env. Pollution. Mon, pp 165
# for Min Variance Unbiased ests of parameters of lognormal(mu,var=s2) distn
        psi <- 0
        psi[1] <- ((n - 1) * t)/n
        for(i in 1:25) {
                psi[i + 1] <- (psi[i] * (n - 1)^2 * t)/((i + 1) * n * (n + (2 *
                        i - 1)))
                if(abs((psi[i + 1] - psi[i])/psi[i]) < 1e-09)
                        break
        }
        psi <- 1 + sum(psi)
        psi
}
```

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