

Surface Soil Radionuclides and Inorganic Chemicals

Introduction

Results reported herein are from soil samples collected during 1999 and 2000 from a grid of 16 locations surrounding the WIPP site (the Near Field grid) and a grid of 16 locations approximately 12 miles southeast of the WIPP (the Cactus Flats grid, Fig. 2). The 2000 soil samples were collected prior to the arrival of the first mixed waste shipments at WIPP. Thus, the data for the non-radioactive analytes represent a continuation of the baseline monitoring study whereas the radionuclide data for the 2000 soil samples are results from the first monitoring phase. Measurements presented herein were made by CEMRC on the 2000 soil samples for ^{234}U , ^{235}U , ^{238}U , ^{230}Th , ^{232}Th , ^{228}Th and $^{239,240}\text{Pu}$, ^{137}Cs , ^{208}Tl , ^{212}Pb , ^{212}Bi , ^{214}Pb , ^{228}Ac , $^{234\text{m}}\text{Pa}$, ^{241}Am , ^{40}K , ^{60}Co and ^7Be . The natural radionuclides ^{208}Tl , ^{212}Bi , ^{214}Pb and ^{212}Pb are measured after allowing for ingrowth and their concentrations do not represent natural levels in the environment. However, the activity of ^{214}Pb can be used to estimate the original environmental concentration of ^{226}Ra . The activity of ^{208}Tl , ^{212}Bi and ^{212}Pb can be used to estimate activities of other members of the thorium series. Results are also presented for 45 non-radiological analytes measured using ICP-MS, AAS and IC.

One finding presented in the CEMRC 1999 Report was that there were significant differences in many analyte concentrations between the Near Field and Cactus Flats grids. Differences in soil texture were identified as a possible cause for these observations. Therefore, soil texture analyses were conducted on the 2000 soil samples to review these relationships.

Methods

The 16 sampling locations constituting each grid are distributed over approximately 16,580 hectares. In both 1998 and 1999 at each of the 32 locations (grid nodes), soil was collected from three randomly selected sites within a 50-m radius of the selected reference

point. In 2000, one sample was collected at each of the 32 grid nodes. Four additional field duplicates were collected at randomly selected reference points each year. Individual sampling sites were selected on the basis of relatively flat topography, minimum surface erosion and minimum surface disturbance by human or livestock activity. At each sampling site, approximately 20 g of soil were removed using a plastic trowel from near the center of each of two 25-cm x 25-cm areas and placed in a plastic bag for inorganic analyses. In addition, approximately 8 L of soil were collected from within the two sampling areas to a depth of approximately 2 cm for radionuclide analyses. Soil samples were excavated using a trowel and placed in plastic bags for transport and storage. Sampling equipment was cleaned between samples.

Initial preparation of the samples for radiological analyses consisted of passing the soil through a 2-mm sieve to remove rocks, roots and other materials. Samples were then dried at 105°C for 12 hours and ground using a jar mill. Approximately 300-mL aliquots were used for gamma spectroscopy analysis. The samples for gamma analysis were sealed in a ~ 300-mL can and stored for at least 21 days to allow radon progeny to reach equilibrium with parent radionuclides.

Gamma spectroscopy analysis was conducted using high purity Ge (HPGe) detector systems for 2-3 days. A set of soil matrix standards was prepared using NIST traceable solutions and used to establish matrix-specific calibration and counting efficiencies.

Separate ~ 10-g aliquots of soil were used for actinide analyses. These aliquots were heated in a muffle furnace to combust organic material and spiked with a radioactive tracer to allow determination of the efficiency of extraction. They then underwent dissolution with HF and HCl followed by NaOH fusion of the insoluble residues. Multiple precipitation, co-precipitation and ion-exchange and/or extraction chromatography procedures were then used to separate and purify the desired

elements. The elements of interest were then precipitated with LaF₃, deposited onto filters, mounted and counted on an alpha spectroscopy system. A summary of QA/QC for radioanalyses is presented in Appendix L.

Soil sample aliquots of 0.1 g were analyzed by AAS for As and Se using the soil collected from near the center of the sampling areas. These samples were neither sieved nor ground to prevent potential contamination by metals. ICP-MS was used to analyze samples for Ag, Al, Ba, Be, Ca, Cd, Ce, Co, Cr, Cu, Dy, Er, Eu, Fe, Gd, Hg, K, La, Li, Mg, Mn, Mo, Na, Ni, Pb, Pr, Sb, Sc, Sm, Sn, Sr, Th, Ti, Tl, U, V and Zn. The lower detection limits for both of these systems are in the low parts per billion range (Appendix K). Soil samples were analyzed by IC for chloride, fluoride, nitrate, nitrite, phosphate and sulfate. A summary of QA/QC methods for inorganic analyses is presented in Appendix K. The mean concentrations of these analytes reported herein for soils include only those values that are above detection levels. Thus, some estimates of the mean may be biased toward larger values. Sn and Na are also omitted from the statistical analyses because the level of the analytes in laboratory blanks approached and sometimes exceeded the levels measured in the samples, thus making the interpretation of their concentrations problematic.

Two aliquots of each sample collected in 2000 were air-dried, passed through a 2-mm sieve and analyzed by CEMRC for soil texture using the pipette method (Gee, G. W. and J. W. Bauder, 1986, Particle-size Analysis. In Klute, A. (ed.) *Methods of Soil Analysis. Part I. Physical and Mineralogical Methods-Agronomy Monograph no. 9*. American Society of Agronomy, Madison, WI). These analyses produced data for the percentages of sand, silt and clay in the soils.

Multivariate analysis of variance (MANOVA) was used to test for differences between the Cactus Flats and Near Field grids across inorganic analytes and soil particle size. MANOVA was also used to test for differences between 1999 and 2000, with Tukey's Honest Significant Difference Test used to identify differences between means of individual analytes. Chloride, Hg, Na, nitrite, Sn, Se, Tl and V were eliminated from the

MANOVA for the 1999 data because those analytes had a preponderance of values below detection levels. Because of the lower number of samples collected in 2000 as compared to 1999 (36 versus 100, respectively), MANOVA could not be conducted using all of the analytes. Therefore the inorganic analytes were assigned to the following groups: anions (chloride, fluoride, nitrate, phosphate and sulfate), lanthanides (Ce, Dy, Er, Eu, Gd, La, Nd, Pr, Sm, Th and U) and other metals (Ag, Al, As, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Mo, Ni, Pb, Sb, Sc, Sr, Ti, Tl, V and Zn). The analytes nitrite, Se and Hg were not included in the analyses of the 2000 soils because too few measurements were above detection levels.

MANOVA was used to test for differences between grids and between years (1998 and 2000) in the radionuclides. The radionuclides ²⁴¹Am, ^{234m}Pa, ²³⁴U, ²³⁵U and ²³⁸U were not included in these analyses due to the number of non-detect values.

Correlations of the concentrations of radionuclides to soil texture classes and to concentrations of Al and Pb were computed using Pearson correlation coefficients.

Reproducibility of the measurements for the non-radiological measurements was determined from comparing five sets of laboratory duplicates. Relative Percent Differences (RPDs) were computed for all pairs for which the measurements were greater than the Minimum Detectable Concentration (MDC). The RPD is calculated as

$$RPD = 2 \frac{|c_1 - c_2|}{c_1 + c_2} \times 100\%$$

where c_i is the concentration of the i^{th} duplicate. The RPD is the difference divided by the mean of two values expressed as a percent.

Reproducibility of the measurements of radionuclides was determined by comparing measurements from four sets of laboratory duplicates. Relative Error Ratios (RERs) were computed for all measurements for which concentrations were greater than the MDC. RER is computed as

$$RER = \frac{|c_1 - c_2|}{\sqrt{s_1^2 + s_2^2}}$$

where c_i is the concentration of the i^{th} duplicate and s_i is the estimated standard deviation of the i^{th} concentration, where the standard deviation incorporates counting uncertainty and uncertainties associated with other aspects of the instrument measurements. Relative error ratios are used in addition to RDPs when comparing duplicate samples of radionuclides because they take into account counting and other uncertainties that are associated with activity measurements. RERs were computed for ^{137}Cs , ^{208}Tl , ^{212}Bi , ^{212}Pb , ^{214}Bi , ^{214}Pb , ^{228}Ac and ^{40}K .

Results and Discussion

Particle-Size Analysis

Differences between the Near Field and Cactus Flats grids in concentrations of many analytes were documented in the 1999 CEMRC Report. These differences were postulated to arise from the preferential association of many analytes with fine (silt and clay) soil particles combined with a differential in soil texture between the two grids. The particle-size analysis for the 1998 soils employed the hydrometer method. The 2000 soils were analyzed using the pipette analysis because it provides greater accuracy than the hydrometer method. The average relative percent difference between duplicate aliquots was 6% for clay, 16% for silt and < 1% for sand. The differences in reproducibility by particle-size fraction are due in part to the predominance of sand in the soils. MANOVA on the texture data for the 2000 soil samples confirmed that there are significant ($p < 0.0001$) differences between the grids in soil texture. The mean percentages of clay (4.54) and of silt (3.64) particles in the soils on the Cactus Flats grid are greater than those on the Near Field grid (2.98 and 1.91 for clay and silt, respectively).

Reproducibility of Measurements

The average RPDs for the non-radiological analytes excluding Sn and Na ranged from 7% to 70% (Table 8). The maximum RPD values

ranged from 12% to 170%. The RPDs reflect the uncertainty in estimated concentrations due to variability in analysis and heterogeneity in the samples. Heterogeneity in the non-radiological samples was probably high because of the relatively small aliquots analyzed and because the samples were not ground. The average RPD value is appropriate for estimating the reproducibility on the average of several samples, whereas the maximum RPD is a conservative estimate of the uncertainty in reproducibility that could be observed on any single measurement.

The measurements of radionuclides in laboratory duplicates were generally in good agreement. RPDs ranged between 1% and 47%. RPDs hold meaning only when the RERs are relatively low, i.e. when the differences do not fall within the range of analytical uncertainty. The maximum RER was 0.21 for the radionuclides measured by gamma analysis. The RERs for the actinides measured by alpha spectroscopy were 5.16 for ^{228}Th , 2.71 for ^{230}Th , 3.40 for ^{232}Th , 1.29 for ^{234}U , 0.65 for ^{235}U , 0.23 for ^{238}U , 2.74 for $^{239,240}\text{Pu}$ and 1.13 for ^{241}Am . The RERs for the gamma-emitting radionuclides compare well to the RERs determined for gamma measurements in Evans et al. (2000, *Waste Isolation Pilot Plant 1999 Site Environmental Report*, DOE/WIPP-00-2225). Evans et al. compared duplicates only for the actinides $^{233,234}\text{U}$ and ^{238}U because their other actinide measurements were below detection limits. The maximum CEMRC RERs for $^{233,234}\text{U}$ and ^{238}U (1.29 and 0.23, respectively) were similar to those reported by Evans et al.

Analyses of Variance

MANOVA showed a significant ($p < 0.0001$) effect of year on the concentrations of the inorganic analytes. The concentrations of the inorganic analytes in the 1999 soils are similar to those measured in the 1998 soils, with only Ag and Tl showing significantly different concentrations (higher and lower, respectively) in 1999 as compared to 1998. However, concentrations of 11 analytes (Ag, Al, As, Cr, Fe, K, Li, Mg, Mn, phosphate, and U) in the 2000 soils showed higher values than 1998 concentrations whereas the concentration of Tl was significantly lower in 2000 as

compared to 1998 (Figs. 19 and 20). Cd had a significantly higher concentration in 1999 than in 2000.

It is believed that most of these differences between years are due to changes in the sample preparation procedures. In 2000 the digestion procedure was modified to use a microwave instead of a hotplate, as had been used in the 1998 and 1999 analyses. The microwave appears to be much more effective in dissolving some analytes. However, the lower concentration of Tl in 1999 and 2000 as compared to 1998 and of Cd in 2000 as compared to 1999 cannot be explained by this change in methodology.

The average MDC for radionuclides in soils determined by alpha spectroscopy was ≈ 0.1 mBq g⁻¹. The average MDC for radionuclides determined by gamma spectrometry was ≈ 1.3 mBq g⁻¹. MANOVA showed a significant ($p < 0.001$) year effect on radionuclide concentrations as well. However, there were no significant differences between years in the concentrations of the individual radionuclides and those differences were relatively small. The largest relative percent difference (RPD) between the adjusted means from the MANOVA was 11% for ¹³⁷Cs. Most of the radionuclides showed lower concentrations in 2000 than in 1998, with only ²²⁸Ac and ²¹²Bi showing slightly higher values. Concentrations of ^{239,240}Pu were nearly identical between years. Thus the year effect identified in the MANOVA probably arises from relatively consistent but small differences between years. Given that (1) the uncertainty on individual measurements ranged between 1.6% and 44% of the reported values, (2) these uncertainties cannot be considered in the MANOVA, (3) there were no significant differences between years in the mean concentrations of any radionuclide and (4) the data from the Fixed Air Sampler in the exhaust shaft showed no indications of a release, it seems unlikely that the between-year differences are associated with the receipt of waste at the WIPP.

Results of the MANOVA on the 1999 soil samples showed that there were significant ($p < 0.0001$) differences between the two grids, and that the Cactus Flats grid generally had higher concentrations of metals than at the

Near Field grid (Table 9). Of the analytes, 27 (Ag, Al, Ba, Be, Cd, Ce, Co, Cr, Cu, Dy, Er, Eu, Fe, Gd, K, La, Li, Mn, Mo, Nd, Pb, Pr, Sm, Sr, Th, Ti, and U) showed significantly ($p < 0.05$) higher concentrations on the Cactus Flats grid as compared to the Near Field grid. Nitrate showed a significantly lower concentration on the Cactus Flats grid.

MANOVA showed a significant ($p < 0.0001$) grid effect on the lanthanide analytes in the 2000 soil samples (Table 10). All of the lanthanides had significantly ($p < 0.05$) greater concentrations in the Cactus Flats soils than in the Near Field soils. MANOVA showed that there was no significant grid effect on the anions, although chloride and sulfate individually showed significantly higher concentrations on the Near Field grid as compared to the Cactus Flats grid. MANOVA also did not show a grid effect on the non-lanthanide metal concentrations, although individually Al, Ba, Be, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Ni, Pb, Sc, Ti, V and Zn showed significantly ($p < 0.05$) higher concentrations on the Cactus Flats grid than on the Near Field grid.

Grid effects were significant ($p < 0.05$) for the 2000 radionuclide concentrations. The concentrations of nine radionuclides (²²⁸Ac, ²¹²Bi, ²¹⁴Bi, ²¹²Pb, ²¹⁴Pb, ²²⁸Th, ²³⁰Th, ²³²Th, and ²⁰⁸Tl) were significantly higher on the Cactus Flats grid than on the Near Field grid (Table 10). Grid effects on the combined 1998 and 2000 data were also significant ($p < 0.0001$). All radionuclides except ⁴⁰K showed significantly higher concentrations on the Cactus Flats grid than on the Near Field grid. These same patterns were observed in baseline studies presented in the CEMRC 1999 Report and in Kirchner et al. (*J. Environ. Rad.*, in press).

Correlation With Soil Texture

The 2000 soil data also show that the concentrations of many analytes are correlated with the proportion of fine (silt + sand) particles in the soil. Of the non-radiological analytes, Al, As, Ba, Be, Ca, Ce, Co, Cr, Cu, Dy, Er, Eu, Fe, Gd, Hg, K, La, Li, Mg, Mn, Mo, Nd, Ni, Pb, Pr, Sc, Sm, Sr, Th, Ti, Tl, U, V and Zn showed significant ($p < 0.05$) positive correlations with the proportion of

fine particles in the soil samples. All of the radionuclides except ^{235}U showed significant ($p < 0.01$) positive correlations with the proportion of fine particles in the soils (Table 11). In the case of ^{235}U , interference from spectral tailing of the ^{234}U peak is likely to have introduced uncertainty into the measurements and thus degraded the correlation. These radionuclides also showed significant ($p < 0.01$) positive correlations with the concentrations of Al and Pb. In all cases soil texture was a better predictor of radionuclide concentrations than was Al. For example, the proportion of fine particles accounted for 35% of the variability in $^{239,240}\text{Pu}$, whereas Al only accounted for 26% of the variability. Lead was a better predictor than soil texture for the isotopes of Pu, Am and U but not for the Th isotopes. The concentration of Pb accounted for 64% of the variability in $^{239,240}\text{Pu}$ as compared with 35% for soil texture.

The importance of soil texture on the dynamics of many soil analytes was described in the CEMRC 1999 Report. Many metals, including radionuclides, are known to have an affinity for small particles in the soil (Muller, R. N. and D. G. Sprugel, 1977, *Health Physics* 33, 405; Muller, R. N. and G. T. Tissue, 1977, *Soil Science* 124, 191; Watters et al., 1983, *Radiochimica Acta* 32, 89; Little, C. A., 1980, *J. Environ. Qual.* 9, 350; Tamura, T., 1975, *J. Environ. Qual.* 4, 350). The aluminosilicates and hydrated oxides of clays usually account for the major adsorptive component of soils and hence affect the binding of radionuclides (Wild, A., 1994, *Soils and the Environment*. Cambridge University Press; Whicker, F. W. and V. Schultz, 1982, *Radioecology: Nuclear Energy and the Environment. Vol. II*. CRC Press).

Clay content also affects the infiltration rate of soils. Infiltration can deplete the inventory of contaminants in the surface layer of soil, with sandy soils generally having greater infiltration rates than clay soils. However, a simple relationship between vertical transport rates and soil texture should not be expected because macropores such as root channels and soil cracks are unlikely to form in sandy soils. Macropore flow is recognized as an extremely important

mechanism in the leaching of contaminants in unsaturated soils (Luxmoore, R. J., 1991, In Gish, T. J., & A. Schirmohammadi (eds.), *Preferential Flow. Proc. Natl. Symp.*, Chicago, IL. 16-17 Dec. 1991. St. Joseph, MI, Am. Soc. Agric. Eng.). Litaor et al. (1998, *J. Environ. Rad.* 38, 17.) concluded that most of the vertical transport of $^{239,240}\text{Pu}$ and ^{241}Am in the top 20 cm of soils at the Rocky Flats Environmental Technology site (Colorado, USA) was associated with infiltration of suspended and colloidal matter, and they implicated macropore flow following heavy rain as an important mechanism for moving Pu and Am deep into the soil. Thus clays in soils, through their adsorptive properties and by their effects on infiltration rates, can impact the vertical movement of many radionuclides and hence influence surface concentrations.

Comparison to Other Studies

The mean activity concentrations of ^{137}Cs , ^{234}U , ^{235}U , ^{238}U , and ^{40}K in CEMRC 2000 samples fell within the ranges reported by Evans et al., (*op. cit.*). The maximum $^{239,240}\text{Pu}$ concentration (0.40 mBq g⁻¹) was within the range reported by Kenny et al. (1995, *Radionuclide Baseline in Soil Near Project Gnome and the Waste Isolation Pilot Plant, EEG-58*) at the WIPP (0-0.74 mBq g⁻¹) and was lower than background concentrations found at Hueston Woods and Urbana, Ohio (0.7-1.0 mBq g⁻¹) (Alberts et al., 1980, *J. Environ. Qual.* 9, 592) and at a series of 15 locations between Ft. Collins and Colorado Springs, Colorado (0.6-1.7 mBq g⁻¹) (Hodge et al., 1996, *Chemosphere* 32, 2067). Evans et al. (*op. cit.*) detected neither $^{239,240}\text{Pu}$ nor ^{241}Am in surface soils.

These results demonstrate that significant variability in background levels of soil contaminants and constituents can occur in areas having relatively low variability in soil texture. The high correlations of the radionuclides and many of the non-radioactive metals to the percentages of silt and clay in the soil explains much of the between-sample variability. Actinides can form strong complexes with oxygen-containing ligands (Beal, G. W. and B. Allard, 1981, In Tewari, P. H. (ed.), *Adsorption from Aqueous Solutions*, Plenum Press, New York; Allard,

B., 1982, In Edlestein, N. M. (ed.), *Actinides in Perspective*, Pergamon Press, Oxford). Actinides also form complexes with humic molecules and these can be significantly more stable than their complexes with simple inorganic ligands (Livens, F. R. and D. L. Singleton, 1991, *J. Environ. Rad.* 13, 323), although subject to a significant concentration effect (Hummel et al., 1999, *Radiochimica Acta* 84, 111). Therefore, the affinity of $^{239,240}\text{Pu}$ for fine soil particles could also be due to organic material in the silt fractions. The radionuclides in the 2000 soil samples also showed significant correlations with Al and Pb, as was noted in the CEMRC 1999 Report for the 1998 data.

These data also suggest that the variability in concentrations across locations may arise from a redistribution of naturally occurring radionuclides and fallout-contaminated fine

soil particles or from a greater degree of entrapment of the contaminants in the upper layer of the soil. Radionuclides deposited as fallout, such as ^{137}Cs and $^{239,240}\text{Pu}$, would be expected to show a decrease in concentration with depth. Soil profile analyses would be expected to help elucidate the dynamics of radionuclide contaminants in soil. However, the soil profile concentrations presented in Evans et al. (*op. cit.*) do not demonstrate a consistent pattern of concentration of radionuclides with respect to depth within the top 10 cm of soil. The collection of additional soil profile data is expected to help determine the underlying causes for the differences observed between the Near Field and Cactus Flats grids.

Tables presenting soil data summarized herein are available on the CEMRC web site at <http://www.cemrc.org>.

Table 8. Mean and Maximum Relative Percent Differences for Inorganic Analytes in Soils

Analyte	Mean ^a RPD (%)	Maximum RPD (%)	Analyte	Mean RPD (%)	Maximum RPD (%)
Ag	22.0	54.9	Mo	36.2	124.3
Al	12.7	33.0	Na	95.1	382.3
As	15.4	46.6	Nd	15.6	32.6
Ba	12.9	26.7	Ni	18.5	30.0
Be	26.9	110.0	Pb	11.1	23.9
Ca	8.5	17.7	Pr	16.3	31.8
Cd	51.4	167.3	Sb	24.8	100.4
Ce	17.9	37.9	Sc	12.9	25.8
Co	18.4	50.6	Se	70.4	170.1
Cr	13.0	30.2	Sm	15.7	31.0
Cu	14.2	47.3	Sn	-12.2	29.1
Dy	15.9	28.9	Sr	13.1	32.9
Er	15.7	26.5	Th	25.6	53.5
Eu	14.5	25.7	Ti	18.5	40.7
Fe	14.1	31.4	Tl	38.2	159.7
Gd	17.7	34.4	U	15.5	29.7
Hg	49.8	130.6	V	16.4	27.4
K	8.0	15.1	Zn	7.4	12.1
La	15.6	30.3	Chloride	49.4	103.5
Li	8.7	15.6	Nitrate	20.2	34.2
Mg	12.8	25.3	Phosphate	17.4	39.7
Mn	11.1	24.2	Sulfate	13.6	25.6

^a $RPD = 2 \frac{|c_1 - c_2|}{c_1 + c_2} \times 100\%$, where c_1 and c_2 are concentrations in the duplicate samples

**Table 9. Summary Statistics for Inorganic Analytes
in Soil Samples Collected in 1999**

Analyte	Units	Near Field			Cactus Flats		
		^a N	^b Mean	Range	N	Mean	Range
Ag	mg kg ⁻¹	43	1.4E-02	5.7E-03 - 3.3E-02	38	2.2E-02	5.7E-03 - 3.3E-02
Al	mg kg ⁻¹	50	2.1E+03	1.6E+02 - 5.0E+03	49	2.7E+03	1.6E+02 - 5.0E+03
As	mg kg ⁻¹	51	9.6E-01	5.0E-01 - 1.9E+00	43	1.2E+00	5.0E-01 - 1.9E+00
Ba	mg kg ⁻¹	51	2.0E+01	8.1E+00 - 5.1E+01	49	2.7E+01	8.1E+00 - 5.1E+01
Be	mg kg ⁻¹	49	1.1E-01	4.8E-02 - 2.6E-01	49	1.4E-01	4.8E-02 - 2.6E-01
Ca	mg kg ⁻¹	45	4.9E+02	1.7E+02 - 2.0E+03	33	8.1E+02	1.7E+02 - 2.0E+03
Cd	mg kg ⁻¹	47	5.5E-02	3.0E-02 - 1.4E-01	42	8.0E-02	3.0E-02 - 1.4E-01
Chloride	mg kg ⁻¹	35	1.7E+00	6.0E-01 - 1.4E+01	46	1.1E+00	6.0E-01 - 1.4E+01
Co	mg kg ⁻¹	49	6.6E-01	3.2E-01 - 1.7E+00	50	8.7E-01	3.2E-01 - 1.7E+00
Cr	mg kg ⁻¹	50	3.0E+00	1.6E+00 - 6.9E+00	50	4.1E+00	1.6E+00 - 6.9E+00
Cu	mg kg ⁻¹	48	1.8E+00	8.4E-01 - 4.2E+00	50	2.3E+00	8.4E-01 - 4.2E+00
Fe	mg kg ⁻¹	38	2.2E+03	2.3E+02 - 4.3E+03	37	3.9E+03	2.3E+02 - 4.3E+03
Hg	mg kg ⁻¹	30	3.3E-03	1.4E-03 - 1.6E-02	40	3.1E-03	1.4E-03 - 1.6E-02
K	mg kg ⁻¹	49	5.8E+02	2.2E+02 - 1.4E+03	48	7.2E+02	2.2E+02 - 1.4E+03
La	mg kg ⁻¹	50	2.9E+00	1.6E+00 - 6.0E+00	49	4.0E+00	1.6E+00 - 6.0E+00
Li	mg kg ⁻¹	50	1.8E+00	7.8E-01 - 5.0E+00	50	2.2E+00	7.8E-01 - 5.0E+00
Mg	mg kg ⁻¹	49	4.6E+02	1.7E+02 - 1.1E+03	41	5.0E+02	1.7E+02 - 1.1E+03
Mn	mg kg ⁻¹	50	3.9E+01	1.7E+01 - 8.5E+01	49	5.2E+01	1.7E+01 - 8.5E+01
Mo	mg kg ⁻¹	49	7.8E-02	4.0E-02 - 1.5E-01	43	1.1E-01	4.0E-02 - 1.5E-01
Na	mg kg ⁻¹	8	7.9E+01	6.5E+01 - 1.2E+02	6	7.1E+01	6.5E+01 - 1.2E+02
Ni	mg kg ⁻¹	47	1.7E+00	4.7E-01 - 4.8E+00	40	1.8E+00	4.7E-01 - 4.8E+00
Nitrate	mg kg ⁻¹	52	1.3E+01	1.2E+00 - 7.0E+01	55	8.6E+00	1.2E+00 - 7.0E+01
Nitrite	mg kg ⁻¹	6	1.7E-01	1.0E-01 - 2.3E-01	15	2.9E+00	1.0E-01 - 2.3E-01
Pb	mg kg ⁻¹	48	2.8E+00	1.4E+00 - 5.6E+00	49	3.9E+00	1.4E+00 - 5.6E+00
Phosphate	mg kg ⁻¹	52	5.4E+00	3.1E-01 - 1.3E+01	54	6.3E+00	3.1E-01 - 1.3E+01
Sb	mg kg ⁻¹	38	5.6E-02	2.1E-02 - 2.3E-01	42	5.7E-02	2.1E-02 - 2.3E-01
Se	mg kg ⁻¹	4	1.4E-01	1.3E-01 - 1.4E-01	5	1.5E-01	1.3E-01 - 1.4E-01
Sr	mg kg ⁻¹	49	3.3E+00	1.5E+00 - 7.4E+00	48	4.4E+00	1.5E+00 - 7.4E+00
Sulfate	mg kg ⁻¹	52	3.8E+00	7.9E-01 - 1.4E+01	55	4.6E+00	7.9E-01 - 1.4E+01
Th	mg kg ⁻¹	49	1.1E+00	5.6E-01 - 2.3E+00	49	1.5E+00	5.6E-01 - 2.3E+00
Ti	mg kg ⁻¹	49	5.8E+01	2.9E+01 - 1.8E+02	49	7.4E+01	2.9E+01 - 1.8E+02
U	mg kg ⁻¹	50	9.0E-02	4.7E-02 - 2.2E-01	50	1.1E-01	4.7E-02 - 2.2E-01
V	mg kg ⁻¹	45	4.1E+00	2.0E+00 - 1.3E+01	33	5.1E+00	2.0E+00 - 1.3E+01
Zn	mg kg ⁻¹	48	1.1E+01	2.8E+00 - 4.0E+01	50	1.2E+01	2.8E+00 - 4.0E+01

^aN = number of samples > MDC

^bMean = arithmetic mean

**Table 10. Summary Statistics for Analytes
in Soil Samples Collected in 2000**

Analyte	Unit	Near Field			Cactus Flats		
		^a N	^b Mean	Range	N	Mean	Range
Ag	mg kg ⁻¹	18	1.4E-02	7.3E-03 - 4.3E-02	18	1.8E-02	6.6E-03 - 6.1E-02
Al	mg kg ⁻¹	18	3.7E+03	1.8E+03 - 6.0E+03	18	5.3E+03	2.4E+03 - 9.2E+03
As	mg kg ⁻¹	18	1.4E+00	7.4E-01 - 3.6E+00	18	2.0E+00	1.0E+00 - 4.0E+00
Ba	mg kg ⁻¹	18	2.1E+01	1.0E+01 - 4.2E+01	18	3.0E+01	1.8E+01 - 4.3E+01
Be	mg kg ⁻¹	18	1.3E-01	8.7E-02 - 2.4E-01	18	1.8E-01	9.2E-02 - 2.5E-01
Ca	mg kg ⁻¹	18	9.0E+02	3.5E+02 - 5.7E+03	18	8.2E+02	2.8E+02 - 2.3E+03
Cd	mg kg ⁻¹	18	5.6E-02	2.0E-02 - 2.9E-01	18	5.8E-02	2.8E-02 - 9.6E-02
^c Ce	mg kg ⁻¹	18	6.1E+00	4.0E+00 - 9.0E+00	18	8.1E+00	4.9E+00 - 1.4E+01
^d Chloride	mg kg ⁻¹	18	5.7E+00	1.0E+00 - 2.0E+01	18	2.3E+00	-5.9E-01 - 5.9E+00
Co	mg kg ⁻¹	18	7.3E-01	4.2E-01 - 1.3E+00	18	9.7E-01	5.3E-01 - 1.7E+00
Cr	mg kg ⁻¹	18	4.2E+00	2.6E+00 - 5.3E+00	18	5.3E+00	3.1E+00 - 8.6E+00
Cu	mg kg ⁻¹	18	1.5E+00	7.3E-01 - 2.5E+00	18	2.0E+00	1.0E+00 - 3.2E+00
^c Dy	mg kg ⁻¹	18	3.0E-01	2.0E-01 - 4.8E-01	18	4.3E-01	2.6E-01 - 6.8E-01
^c Er	mg kg ⁻¹	18	1.5E-01	9.7E-02 - 2.3E-01	18	2.1E-01	1.2E-01 - 3.4E-01
^c Eu	mg kg ⁻¹	18	1.0E-01	6.4E-02 - 1.9E-01	18	1.5E-01	9.4E-02 - 2.3E-01
Fe	mg kg ⁻¹	18	3.7E+03	1.8E+03 - 5.3E+03	18	5.3E+03	3.1E+03 - 7.7E+03
^d Fluoride	mg kg ⁻¹	18	5.9E-01	-9.2E-02 - 2.2E+00	18	7.4E-01	2.5E-01 - 1.5E+00
^c Gd	mg kg ⁻¹	18	6.7E-01	4.2E-01 - 1.0E+00	18	9.3E-01	4.9E-01 - 1.7E+00
Hg	mg kg ⁻¹	13	4.8E-03	3.5E-03 - 1.0E-02	17	5.2E-03	3.3E-03 - 8.4E-03
K	mg kg ⁻¹	18	8.0E+02	5.4E+02 - 1.3E+03	18	1.1E+03	3.9E+02 - 2.7E+03
^c La	mg kg ⁻¹	18	3.3E+00	2.2E+00 - 4.7E+00	18	4.7E+00	3.1E+00 - 7.5E+00
Li	mg kg ⁻¹	18	3.7E+00	2.4E+00 - 5.2E+00	18	4.8E+00	2.2E+00 - 6.8E+00
Mg	mg kg ⁻¹	18	5.8E+02	3.9E+02 - 1.1E+03	18	7.5E+02	3.2E+02 - 1.7E+03
Mn	mg kg ⁻¹	18	4.7E+01	2.7E+01 - 7.7E+01	18	6.6E+01	3.4E+01 - 1.3E+02
Mo	mg kg ⁻¹	18	1.0E-01	5.6E-02 - 1.9E-01	18	1.3E-01	8.4E-02 - 2.2E-01
^c Nd	mg kg ⁻¹	18	3.1E+00	2.0E+00 - 4.6E+00	18	4.4E+00	2.9E+00 - 7.0E+00
Ni	mg kg ⁻¹	18	2.0E+00	1.1E+00 - 3.3E+00	18	2.4E+00	1.2E+00 - 4.2E+00
^d Nitrate	mg kg ⁻¹	18	1.8E+01	5.7E+00 - 4.5E+01	18	1.0E+01	3.2E+00 - 4.2E+01
Nitrite	mg kg ⁻¹	5	2.3E-01	8.6E-02 - 4.4E-01	2	2.5E-01	2.4E-01 - 2.7E-01
Pb	mg kg ⁻¹	18	2.8E+00	1.6E+00 - 4.5E+00	18	4.0E+00	2.6E+00 - 6.0E+00
^d Phosphate	mg kg ⁻¹	18	7.1E+00	3.6E+00 - 1.1E+01	18	6.3E+00	2.6E+00 - 1.2E+01
^c Pr	mg kg ⁻¹	18	8.6E-01	5.5E-01 - 1.2E+00	18	1.2E+00	7.9E-01 - 1.9E+00
Sb	mg kg ⁻¹	18	6.2E-02	3.1E-02 - 1.0E-01	18	7.8E-02	9.7E-03 - 1.4E-01
Sc	mg kg ⁻¹	18	5.7E-01	3.4E-01 - 1.0E+00	18	7.8E-01	3.8E-01 - 1.3E+00
Se	mg kg ⁻¹	10	1.2E+00	6.1E-02 - 5.6E+00	15	7.5E-01	6.2E-02 - 5.0E+00
^c Sm	mg kg ⁻¹	18	5.7E-01	3.7E-01 - 8.5E-01	18	8.1E-01	5.3E-01 - 1.3E+00
Sr	mg kg ⁻¹	18	4.2E+00	2.6E+00 - 8.7E+00	18	5.0E+00	2.5E+00 - 9.0E+00
^d Sulfate	mg kg ⁻¹	18	1.3E+01	5.2E+00 - 3.5E+01	18	6.4E+00	4.1E+00 - 1.2E+01
^c Th	mg kg ⁻¹	18	1.1E+00	7.6E-01 - 1.8E+00	18	1.7E+00	1.1E+00 - 2.4E+00

Table continued on next page

**Table 10. Summary Statistics for Analytes
in Soil Samples Collected in 2000 (Cont.)**

Analyte	Unit	Near Field			Cactus Flats		
		^a N	^b Mean	Range	N	Mean	Range
Ti	mg kg ⁻¹	18	6.0E+01	2.7E+01 - 9.1E+01	18	8.1E+01	3.5E+01 - 1.9E+02
Tl	mg kg ⁻¹	18	5.2E-02	2.8E-02 - 1.4E-01	18	6.2E-02	3.0E-02 - 1.2E-01
^c U	mg kg ⁻¹	18	1.2E-01	7.5E-02 - 2.0E-01	18	1.6E-01	9.8E-02 - 2.3E-01
V	mg kg ⁻¹	18	5.5E+00	3.9E+00 - 7.5E+00	18	7.1E+00	4.5E+00 - 9.1E+00
Zn	mg kg ⁻¹	18	7.1E+00	3.4E+00 - 1.2E+01	18	9.8E+00	5.2E+00 - 1.5E+01
¹³⁷ Cs	mBq g ⁻¹	17	3.8E+00	7.2E-01 - 6.9E+00	18	4.8E+00	8.1E-01 - 1.1E+01
²⁰⁸ Tl	mBq g ⁻¹	18	2.7E+00	1.8E+00 - 3.8E+00	18	3.4E+00	2.7E+00 - 4.6E+00
²¹² Bi	mBq g ⁻¹	18	9.3E+00	6.4E+00 - 1.3E+01	18	1.2E+01	8.3E+00 - 1.5E+01
²¹² Pb	mBq g ⁻¹	18	8.3E+00	5.9E+00 - 1.2E+01	18	1.1E+01	8.4E+00 - 1.4E+01
²¹⁴ Bi	mBq g ⁻¹	18	8.1E+00	5.5E+00 - 1.1E+01	18	1.0E+01	7.5E+00 - 1.3E+01
²¹⁴ Pb	mBq g ⁻¹	18	8.4E+00	6.3E+00 - 1.1E+01	18	1.0E+01	7.8E+00 - 1.4E+01
²²⁸ Ac	mBq g ⁻¹	18	8.8E+00	6.3E+00 - 1.2E+01	18	1.2E+01	8.5E+00 - 1.6E+01
⁴⁰ K	mBq g ⁻¹	18	2.2E+02	1.4E+02 - 2.8E+02	18	2.2E+02	1.5E+02 - 2.8E+02
²⁴¹ Am	mBq g ⁻¹	15	4.5E-02	1.5E-02 - 8.5E-02	18	6.3E-02	2.7E-02 - 1.0E-01
^{239,240} Pu	mBq g ⁻¹	18	1.4E-01	3.9E-02 - 3.9E-01	22	1.8E-01	3.5E-02 - 4.0E-01
²²⁸ Th	mBq g ⁻¹	15	8.7E+00	6.2E+00 - 1.5E+01	19	1.2E+01	5.5E+00 - 1.7E+01
²³⁰ Th	mBq g ⁻¹	15	8.8E+00	6.6E+00 - 1.3E+01	19	1.2E+01	5.3E+00 - 1.6E+01
²³² Th	mBq g ⁻¹	15	8.3E+00	5.8E+00 - 1.4E+01	19	1.1E+01	5.2E+00 - 1.6E+01
²³⁴ U	mBq g ⁻¹	6	7.0E+00	5.3E+00 - 8.6E+00	8	8.1E+00	7.2E+00 - 9.2E+00
²³⁵ U	mBq g ⁻¹	6	4.1E-01	2.7E-01 - 6.0E-01	9	4.3E-01	3.7E-01 - 5.3E-01
²³⁸ U	mBq g ⁻¹	6	7.2E+00	5.4E+00 - 8.9E+00	11	8.1E+00	7.1E+00 - 9.4E+00

^aN = number of samples > MDC

^bMean = arithmetic mean

^cIncluded in lanthanide group for MANOVA

^dIncluded in anion group for MANOVA. Nitrite excluded because of low number of concentrations > MDC

Table 11. Mean Concentrations of Radionuclides and Correlations with Soil Texture, Al and Pb in Soils Collected from Near Field and Cactus Flats Grids in 2000

Analyte	Activity Concentration		^c N	Correlation Coefficients (r)		
	^a Mean (mBq g ⁻¹)	^b SE (mBq g ⁻¹)		Concentration of Al	Concentration of Pb	% Fine Soil Particles
²²⁸ Ac	1.0E+01	3.8E-01	36	0.80	0.90	0.92
²⁴¹ Am	5.5E-2	4.0E-3	33	0.57	0.80	0.66
²¹² Bi	1.1E+01	3.5E-01	36	0.66	0.81	0.75
²¹⁴ Bi	9.1E+00	3.1E-01	36	0.79	0.90	0.89
¹³⁷ Cs	4.3E+00	3.6E-01	35	0.50	0.81	0.62
⁴⁰ K	2.2E+02	6.2E+00	36	0.62	0.73	0.69
²¹² Pb	9.5E+00	3.5E-01	36	0.80	0.93	0.93
²¹⁴ Pb	9.4E+00	2.9E-01	36	0.78	0.91	0.89
^{239,240} Pu	1.6E-01	1.5E-02	41	0.48	0.78	0.57
²²⁸ Th	1.0E+01	5.1E-01	34	0.80	0.85	0.91
²³⁰ Th	1.0E+01	5.0E-01	34	0.79	0.84	0.91
²³² Th	9.9E+00	4.9E-01	34	0.79	0.86	0.91
²⁰⁸ Tl	3.1E+00	1.1E-01	36	0.80	0.90	0.91
²³⁴ U	7.6E+00	2.8E-01	14	0.72	0.86	0.77
²³⁵ U	4.2E-01	2.2E-02	15	<i>^d0.41</i>	<i>0.40</i>	<i>0.39</i>
²³⁸ U	7.8E+00	2.5E-01	17	0.71	0.80	0.78

^aMean = arithmetic mean

^bSE = standard error of mean

^cN = number of samples > MDL

^dItalicized values are not significant. All others are significant at p < 0.01

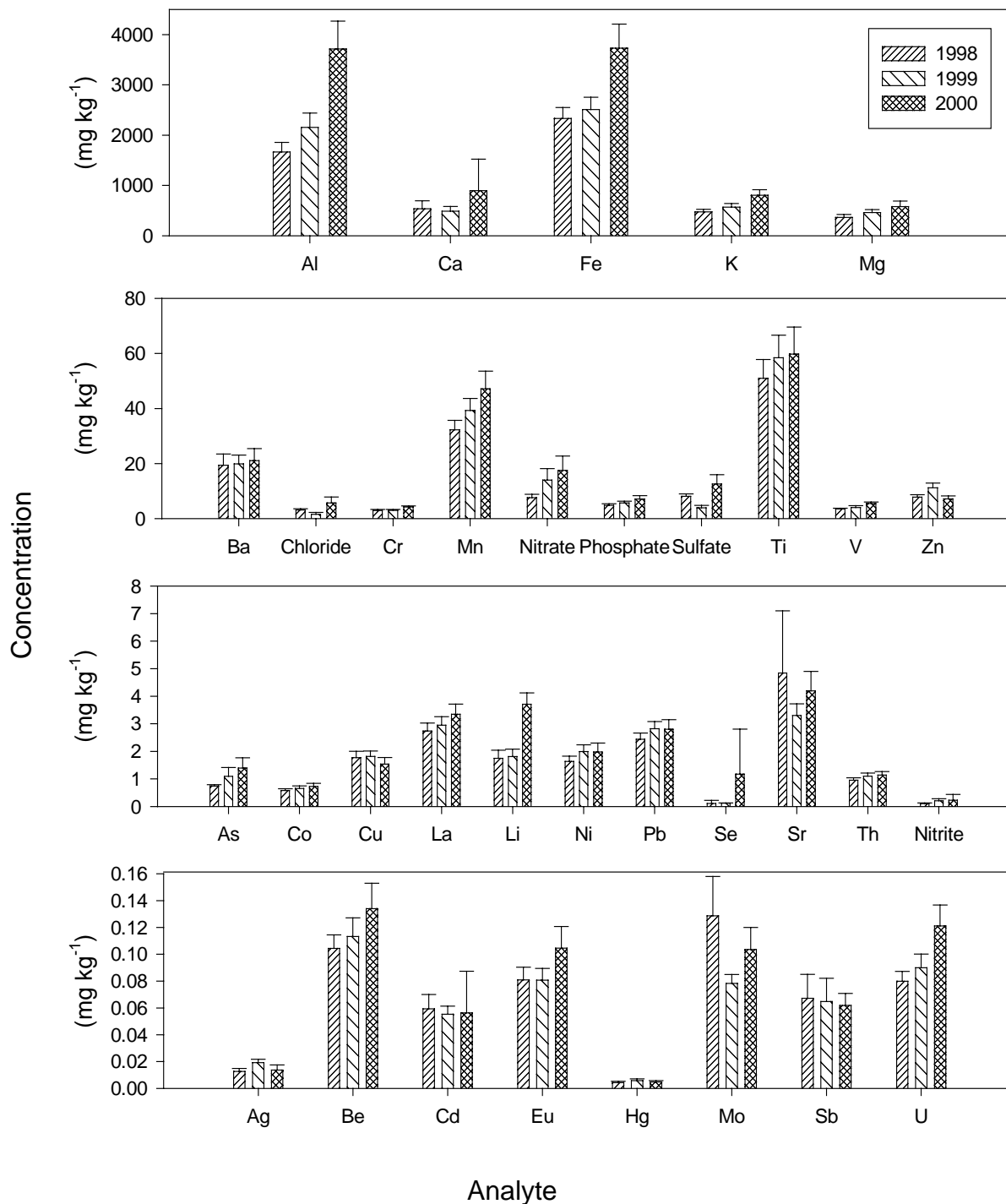


Figure 19. Mean Concentrations of Inorganic Analytes in Soil Samples from Near Field Grid Collected during 1998 - 2000

Error bars show upper 95% confidence intervals for concentrations.

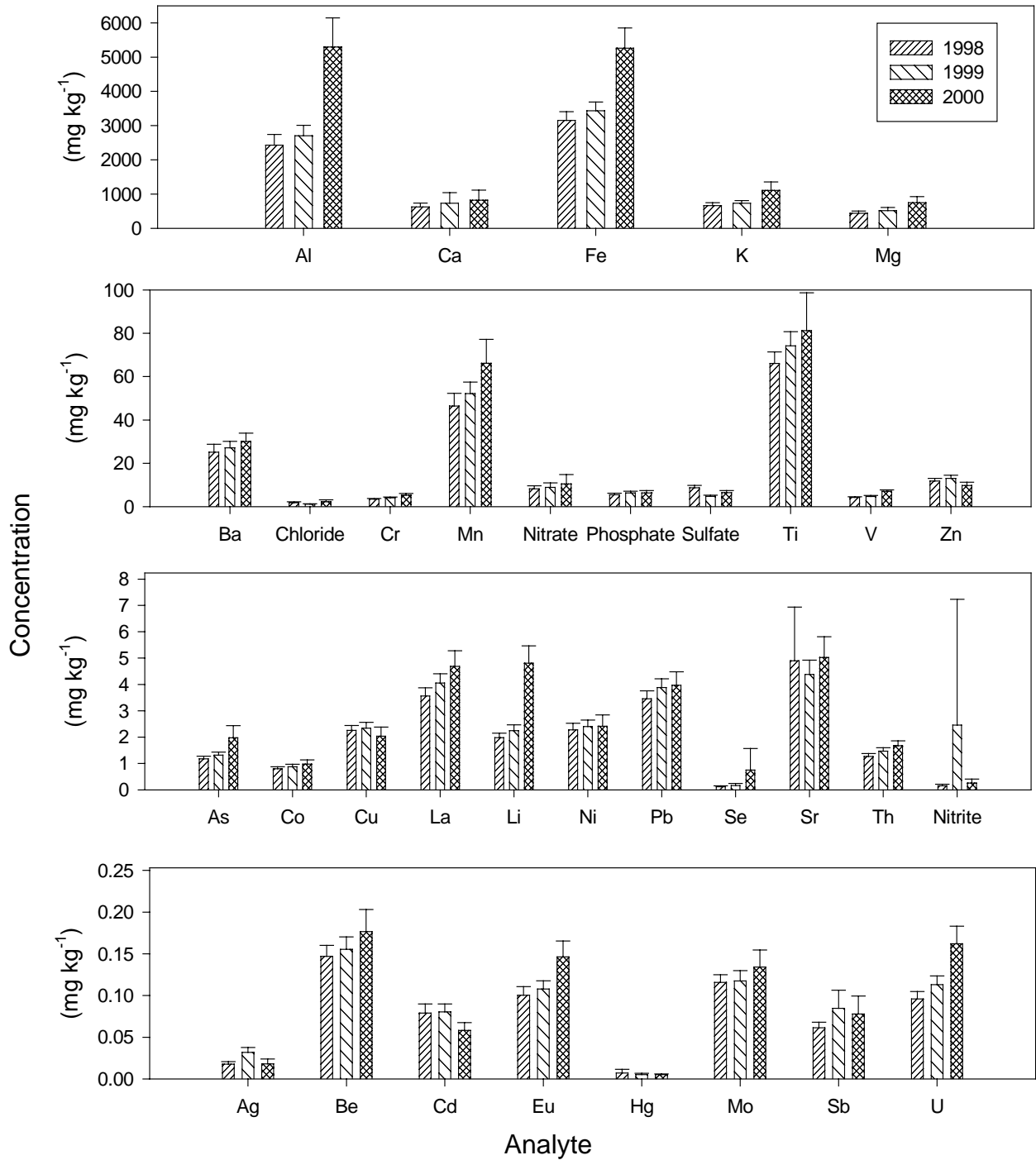


Figure 20. Mean Concentrations of Inorganic Analytes in Soil Samples from Cactus Flats Grid Collected during 1998 - 2000
 Error bars show upper 95% confidence intervals for concentrations.