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Chromium and Major-Element Content of Rocks in the Kirtland Air Force Base Area, Bernalillo County, New Mexico

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FOREWORD

The mission of the New Mexico Environment Department DOE Oversight Bureau is to assure that activities at DOE facilities are protective of the public health and safety and the environment. The Bureau's activities are funded though a grant from the U.S. Department of Energy in accordance with the provisions set forth in the *Agreement-in-Principle between the State of New Mexico and the U.S. Department of Energy*. One of the primary objectives of the agreement is the development and implementation of a program of independent monitoring and oversight.

ABSTRACT

The New Mexico Environment Department oversees environmental activities at U.S. Department of Energy (DOE) facilities in New Mexico. 'Sandia National Laboratories (SNL), one of these DOE facilities, is located on Kirtland Air Force Base (KAFB). The State's oversight task requires extensive knowledge of background concentrations of selected elements in various environmental media.

The chromium content of area rocks is of special interest as chromium is a contaminant or a potential contaminant at several SNL environmental restoration sites. Thus, an investigation was undertaken to determine if high-chromium rocks are present in the KAFB area. The major-element content of samples was also determined to provide additional background geochemistry data.

The highest chromium concentrations for KAFB-area rocks are found in the Tijeras Greenstone. The median chromium content of 13 greenstone samples is 130 ppm; the first and third quartiles are 77 and 361 ppm, respectively. No samples of any of the other rock types have a chromium content exceeding 130 ppm, and only two samples have chromium concentrations > 77 ppm.

Surface exposures of the Tijeras Greenstone are limited to only a small portion of the KAFB area. Therefore, detritus derived from the greenstone belt generally constitutes only a small fraction of KAFB-area sediments. Where little or no greenstone detritus is present, alluvial sediments derived from KAFB-area source rocks are unlikely to contain concentrations of chromium that significantly exceed 100 ppm. Thus, other sources of chromium must be considered to explain the elevated values of chromium found at some SNL environmental restoration sites.

CONTENTS

INTRODUCTION

The New Mexico Environment Department oversees environmental activities at DOE facilities in New Mexico. Sandia National Laboratories (SNL), one of these DOE facilities, is located on Kirtland Air Force Base (KAFB) in Albuquerque. The State's oversight task requires knowledge of background concentrations of selected elements in various environmental media (rocks, soils, ground water, surface water, air). The background investigation for ground water has been completed (Moats and Winn, 1995). Preliminary background studies for soils, surface water, and air are planned or underway. The purpose of this report is to present the results of the background study for rocks.

This investigation was undertaken primarily to determine if high-chromium rocks are present in the KAFB area. The major-element content of samples was also determined to provide additional background geochemistry data. The chromium content of area rocks is of interest as chromium is a contaminant or a potential contaminant in ground water and sediment (includes soil) at several SNL environmental restoration sites (Anonymous, 1993 and Anonymous, 1994). The chemical analysis of KAFB-area rocks is an initial step in an effort to determine whether sediments derived from such rocks would naturally have high chromium contents.

GEOLOGY OF THE KAFB AREA

The KAFB area lies on the east-central margin of the Albuquerque Basin, one of a series of north-south trending structural basins which occupy the Rio Grande Rift. The Manzanita Mountains and the southern end of the Sandia Mountains lie along the eastern boundary of the rift in the KAFB area. The geology of the region has been studied by numerous workers (for example, Reiche, 1949; Myers and McKay, 1970 and 1976; and Kelley, 1977). McCord and others (1994) summarized much of this previous work.

Various Precambrian igneous and metamorphic rocks are exposed in the foothills along the western slopes of the Sandia and Mazanita Mountains. These include, in order of decreasing age, the Tijeras Greenstone, several unnamed units (amphibolite, quartzite, quartzite-schist, biotite-granite, metarhyolite) and the Granite of Sandia Mountains (Sandia Granite). These Precambrian rocks are overlain by Pennsylvanian-Permian sedimentary rocks, which in the KAFB area include chiefly the Sandia Formation and the overlying Los Moyos Limestone (lower part of the Madera Limestone of Myers and McKay, 1970). A generalized geologic map of the KAFB area is shown in Figure 1.

Because high concentrations of chromium and nickel occur almost exclusively in association with mafic and ultramafic rocks (Evans, 1980), metavolcanic rocks within the Tijeras Greenstone belt were especially targeted by this study (Figure 2). The

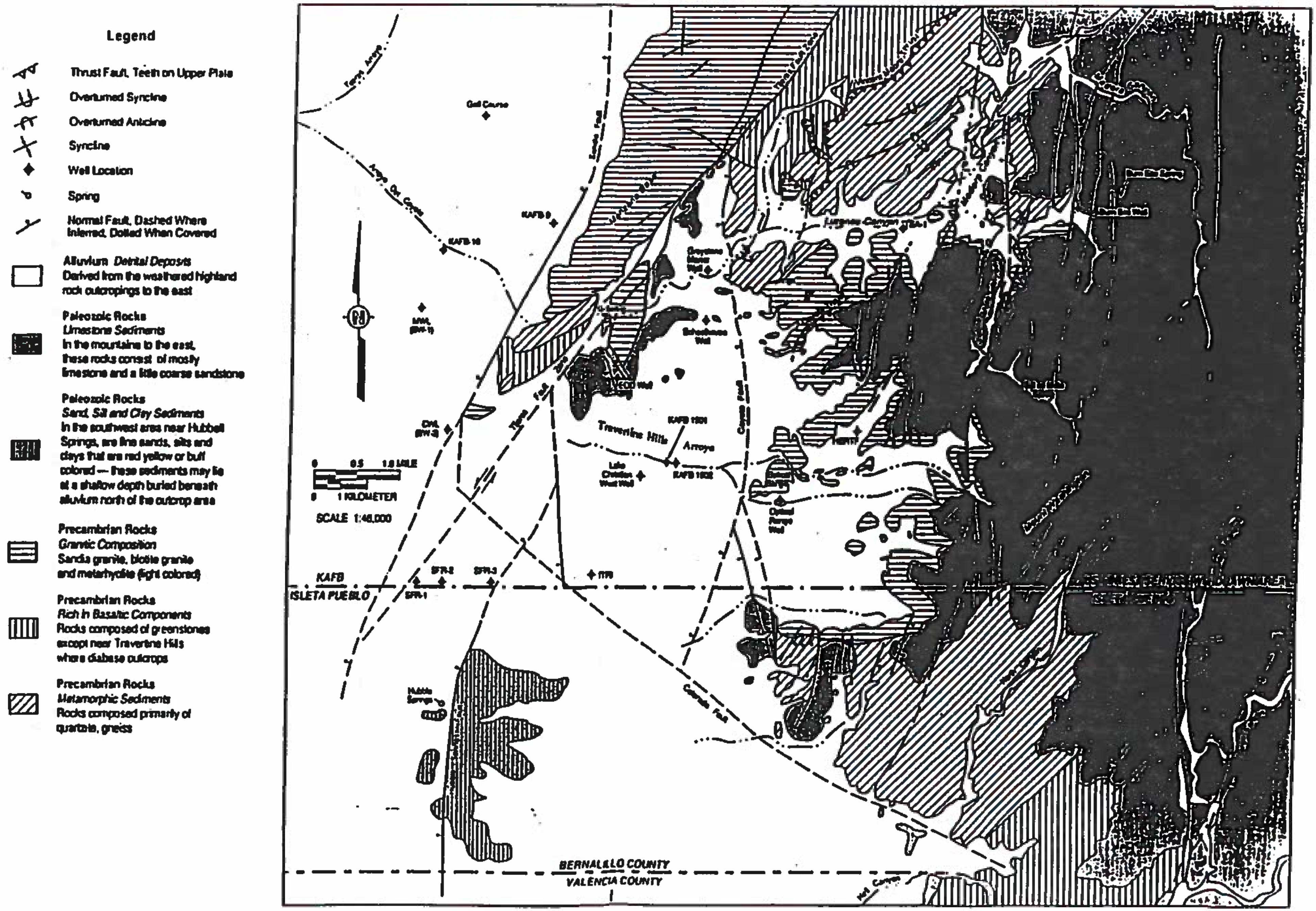

Figure 1. Generalized geologic map of the southern part of the KAFB area (from McCord and others, 1994).

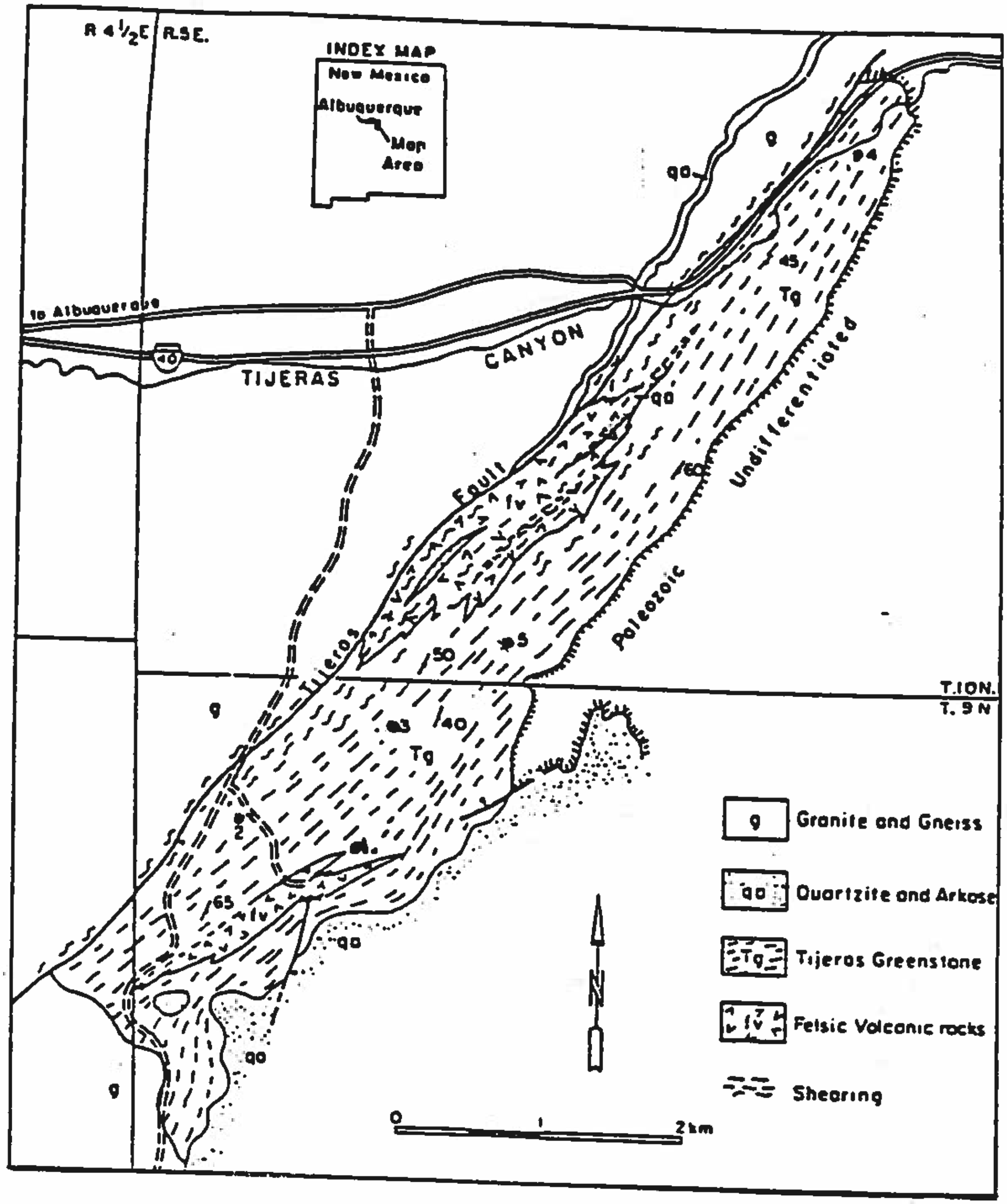

Figure 2. Generalized geologic map showing the Tijeras Greenstone belt (from Condie, 1980). Numbers (1-5) refer to Condie's sample locations.

Tijeras Greenstone consists chiefly of mafic metavolcanic rocks and subordinate arkose, quartzite, and felsic metavolcanic rocks that collectively are exposed in a 1-km wide by 8-km long belt (Condie, 1980). The lowest exposed units are interfingered mafic and felsic volcanic rocks, with some possible hypabyssal intrusives. The Tijeras Greenstone and associated felsic extrusives appear to represent a bimodal volcanic assemblage, which is characteristic of many modern and ancient continental-rift tectonic settings (Condie, 1980).

METHODS

SAMPLING

For this study, 22 samples of KAFB-area rocks were collected at the locations shown in Figure 3:

1 - siltstone from the Los Moyos Limestone,
2 - siltstone from the Sandia Formation,
2 - Sandia Granite,
2 - biotite granite,
1 - quartzite,
3 - quartzite-schist,
1 - amphibolite,
2 - metarhyolite, and
8 - Tijeras Greenstone.
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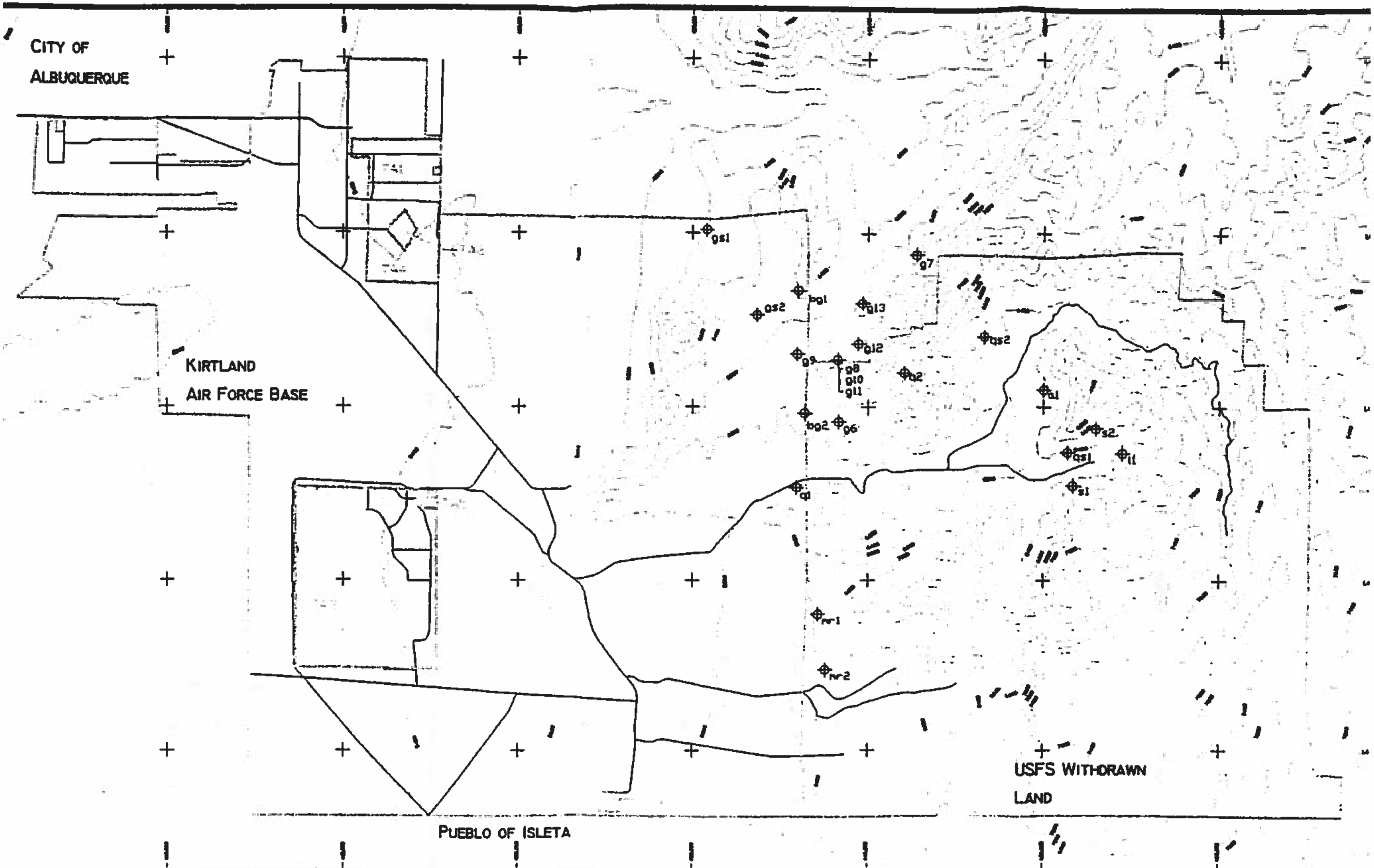
The samples consisted of composites of 10 to 20 chips taken from areas of about 100 ft^2 at each location.

Field work was conducted in two phases, herein denoted as Phase 1 and Phase 2. Phase 1 was implemented in the Fall of 1993; whereas, Phase 2 was conducted in December 1994 to supplement the initial data set. Locations, dates, and rock units involved in the two sampling phases are listed in Tables 1 and 2. Samples g10 and g11 were collected approximately 20 ft apart, at the same location as g8. Sample q2 represents a quartzite bed within the quartzite-schist unit.

ANALYSIS

Samples were prepared and analyzed under contract by the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) laboratory in Socorro. The samples were broken down with a hammer and an aluminum plate, then ground in a Spex Mixer/Mill using a tungsten carbide grinding set. The prepared samples were then analyzed by X-ray fluorescence (XRF) spectrometry. Phase-1 samples were analyzed for chromium, sulfur, and major elements (silicon, titanium, aluminum, iron, magnesium, calcium, manganese, sodium,



EXPLANATION

l1	Los Moyos Limestone
s1-s2	Sandia Formation
gs1-gs2	Sandia Granite
nr1-nr2	metarhyolite
bg1-bg2	biotite granite
qs1-qs2	quartzite schist
q1-q2	quartzite
a1	amphibolite
g1-g13	Tijeras Greenstone

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FIGURE 3

PHASE-I AND PHASE-2

SAMPLE LOCATIONS

potassium, and phosphorus; major elements reported as oxides). Phase-2 samples were analyzed for niobium, zirconium, yttrium, strontium, rubidium, thorium, lead, gallium, zinc, copper, nickel, chromium, vanadium, barium, and major elements.

Table 1
KAFB - Area Rock Sampling Locations, Phase 1

Sample	Rock Type	Location	Date
l1	IPm	SW¼, NE¼, Sec 16, T 9 N, R 5 E	11/05/93
s1	IPs	NE¼, SW¼, Sec 16, T 9 N, R 5 E	10/26/93
s2	IPs	NW¼, NE¼, Sec 16, T 9 N, R 5 E	11/05/93
gs1	pЄgs	NE¼, NE¼, Sec 2, T 9 N, R 4 E	10/26/93
gs2	pЄgs	NE¼, NW¼, Sec 12, T 9 N, R 4 E	10/26/93
bg1	pЄbg	West Border, Sec 1, T 9 N, R 4½ E	10/26/93
bg2	pЄbg	SW¼, Sec 12, T 9 N, R 4 ½ E	10/26/93
q1	pЄq	SE¼, SE¼, Sec 13, T 9 N, R 4 E	10/25/93
qs1	pЄqs	SW¼, NW¼, Sec 16, T 9 N, R 5 E	11/05/93
qs2	pЄqs	NE¼, NW¼, Sec 8, T 9 N, R 5 E	11/05/93
a1	pЄa	NW¼, SW¼, Sec 7, T 9 N, R 5 E	11/05/93
mr1	pЄmr	N½, Sec 25, T 9 N, R 4½ E	10/25/93
mr2	pЄmr	S½, Sec 25, T 9 N, R 4½ E	10/25/93
g6	pЄg	W½, NE¼, Sec 13, T 9 N, R 4½ E	11/08/93
g7	pЄg	SE¼, SW¼, Sec 6, T 9 N, R 5 E	11/08/93
g8	pЄg	N½, SW¼, Sec 12, T 9 N, R 4½ E	11/08/93
g9	pЄg	NE¼, SE¼, Sec 12, T 9 N, R 4 E	11/08/93

Note
Rock unit abbreviations are those of Myers and McKay (1976):

IPm = Los Moyos Limestone
IPs = Sandia Formation
pЄgs = Sandia Granite
pЄbg = biotite granite
pЄq = quartzite
pЄqs = quartzite schist
pЄa = amphibolite
pЄmr = metarhyolite
pЄg = Tijeras Greenstone

Because of fundamental differences between XRF and U. S. Environmental Protection Agency (EPA) SW-846 methods, results of the two techniques are not directly comparable. XRF spectrometry detects essentially all of a given element in a rock sample. In contrast, EPA SW-846 methods will detect only that portion of an element that is readily dissolved by a prescribed acid/hydrogen peroxide leach (Anonymous, 1994).

Like chromium, high concentrations of nickel are more likely to be found in mafic and ultramafic rocks. Thus, Phase-2 samples of Tijeras Greenstone were analyzed for nickel in addition to chromium. With the exception of the sample q2, which was analyzed for trace constituents for quality-control purposes, no other kinds of KAFB-area rocks were analyzed for their nickel content.

Table 2
KAFB - Area Rock Sampling Locations, Phase 2

Sample	Rock Type	Location	Date
q2	p€qs	NE¼, SW¼, Sec 7, T 9 N, R 5 E	12/13/94
g10	p€g	N½, SW¼, Sec 12, T 9 N, R 4½ E	12/13/94
g11	p€g	N½, SW¼, Sec 12, T 9 N, R 4½ E	12/13/94
g12	p€g	SE¼, NE¼, Sec 12, T 9 N, R 4½ E	12/13/94
g13	p€g	SE¼, SE¼, Sec 1, T 9 N, R 4½ E	12/13/94

Note
See Table 1 for rock unit abbreviations.

QUALITY CONTROL

As part of laboratory quality control, triplicate analyses were run on selected samples. More specifically, major elements were analyzed in triplicate for sample g12. Additionally, trace elements were analyzed in triplicate for sample g10. Except for the results for lead, the triplicate values are in good agreement, indicating acceptable laboratory precision.

Steel tools were used to collect the samples. The possibility that chromium levels in some samples may have been inadvertently increased due to abrasion of steel tools was considered. Samples of quartzite are expected to have low chromium contents because of their composition (about 100% quartz). Results for the two quartzite samples (q1 and q2) are 3 to 5 ppm chromium, demonstrating that any contamination that may have been introduced into the samples by the use of steel tools is negligible.

RESULTS

Analytical results for sampling phases 1 and 2 are listed in Appendices A and B, respectively. Geochemical data from Condie (1980), representing 5 samples of Tijeras Greenstone, are included in Appendix C for comparison. Selected data from this study and Condie (1980) are listed in Table 3. Bar graphs showing concentrations of SiO_2, Al_2O_3, Fe_2O_3-T, MgO, CaO, Na_2O, K_2O, Cr, and Ni, respectively, for each rock sample are depicted in Appendix D.

CHROMIUM

The highest chromium concentrations for KAFB-area rocks are found in the Tijeras Greenstone. The 13 samples of Tijeras Greenstone (Table 3 and Appendix D) represent 11 different locations. Analytical results for the 13 samples range from < 3 ppm to 603 ppm. The median chromium content of the greenstone samples is 130 ppm; the first and third quartiles are 77 and 361 ppm, respectively. The low value obtained for sample g6 (< 3 ppm) is a suspected outlier.

Table 3
Compositions of KAFB-Area Rocks

Sample	Rock Type	SiO_2 Wt%	Al_2O_3 Wt%	Fe_2O_3-T Wt%	MgO Wt%	CaO Wt%	Na_2O Wt%	K_2O Wt%	Cr ppm	Ni ppm
l1	IPm	63.0	17.6	5.59	3.91	0.68	0.79	3.32	62	NA
s1	IPs	47.0	14.4	11.6	1.85	3.77	0.31	2.47	108	NA
s2	IPs	73.5	8.50	3.08	1.38	4.87	0.20	1.20	80	NA
gs1	p€gs	68.7	13.1	4.85	1.15	2.57	3.48	4.00	< 3	NA
gs2	p€gs	67.1	12.6	5.67	1.63	2.82	3.86	3.59	< 3	NA
bg1	p€bg	71.1	14.5	2.80	0.37	1.52	3.05	4.22	12	NA
bg2	p€bg	68.1	15.4	2.42	1.12	1.86	3.55	3.98	4	NA
q1	p€q	97.4	0.88	0.37	0.13	0.11	0.17	0.21	3	NA
qs1	p€qs	52.2	25.5	6.87	0.78	0.21	2.21	5.22	74	NA
qs2	p€qs	64.4	20.6	4.26	0.43	0.10	0.50	5.06	69	NA
q2	p€qs	98.0	0.50	0.07	0.08	0.04	< 0.01	0.11	5	4
a1	p€a	64.4	15.1	6.83	2.77	3.49	1.53	1.72	69	NA
mr1	p€mr	72.4	14.1	2.39	0.55	1.68	3.38	4.47	< 3	NA
mr2	p€mr	71.3	13.8	2.73	0.68	1.85	3.23	4.28	< 3	NA
g1	p€g	48.2	12.8	13.5	10.6	10.5	1.36	0.25	381	69
g2	p€g	50.2	12.2	14.7	6.96	9.75	2.36	0.58	85	40
g3	p€g	50.9	11.1	14.4	8.44	9.27	2.94	0.23	77	49
g4	p€g	49.5	11.4	15.1	8.8	8.3	3.32	0.23	73	47
g5	p€g	49.6	11.7	13.9	8.65	10.9	2.10	0.36	130	74
g6	p€g	50.3	11.4	14.4	9.12	7.18	1.73	0.62	< 3	NA
g7	p€g	50.4	10.8	12.3	14.3	6.99	1.91	0.08	84	NA
g8	p€g	71.1	7.74	8.21	4.84	5.42	0.04	0.15	562	NA
g9	p€g	54.1	12.1	12.1	8.71	7.89	2.88	0.28	51	NA
g10	p€g	62.1	9.55	10.5	5.37	8.56	< 0.01	0.01	603	64
g11	p€g	65.6	10.4	8.47	4.66	7.22	< 0.01	0.63	361	51
g12	p€g	55.4	15.1	11.2	6.25	5.49	1.58	0.19	222	42
g13	p€g	50.2	14.2	11.9	8.32	8.32	2.78	0.40	162	92

Notes
See Table 1 for rock unit abbreviations
Samples g1 to g5 are from Condie (1980)
NA means not analyzed.

The chromium content of KAFB-area rocks, other than greenstone, ranges from < 3 to 108 ppm. Of these rock samples, none has a chromium content exceeding 130 ppm, and only two have chromium contents which are > 77 ppm.

MAJOR-ELEMENT CONTENT

Analytical results for major-element contents are consistent with those reported in the literature for the rock types studied. For the purpose of simplification, most KAFB-area rocks can be grouped into three categories based on whole-rock chemistry: greenstone, granitic igneous rocks (consisting of the Sandia Granite, biotite granite, and metarhyolite), and sedimentary/metasedimentary rocks (siltstone, quartzite-schist, and quartzite). Table 4 summarizes the major-element composition for each of these three categories.

Based on the data presented in Table 4, sedimentary/meta-sedimentary rocks in the KAFB area are chemically more similar to granitic rocks than to the Tijeras Greenstone.

Table 4
Major-Element Compositions of KAFB-Area Rocks
Median and Range

Rock Type	SiO_2 Wt%	Al_2O_3 Wt%	Fe_2O_3-T Wt%	MgO Wt%	CaO Wt%	Na_2O Wt%	K_2O Wt%
Greenstone n = 13	50.4 (48.2 - 71.1)	11.4 (9.55 - 13.1)	12.3 (8.21 - 15.1)	8.44 (4.84 - 14.3)	8.3 (5.42 - 10.9)	1.91 (< 0.01 - 3.32)	0.25 (0.01 - 0.63)
Granitic rocks n = 6	69.9 (67.1 - 72.4)	14.0 (13.6 - 15.4)	2.77 (2.39 - 3.67)	0.90 (0.37 - 1.63)	1.86 (1.32 - 2.82)	3.43 (3.05 - 3.86)	4.11 (3.59 - 4.47)
Sedimentary rocks n = 7	64.4 (47.0 - 98.0)	14.4 (0.50 - 25.5)	4.26 (0.07 - 11.6)	0.78 (0.08 - 3.91)	0.21 (0.04 - 4.87)	0.31 (< 0.01 - 2.21)	2.47 (0.11 - 5.22)

Notes
Granitic rocks include pЄgs, pЄbg, and pЄmr
Sedimentary rocks include metasedimentary rocks, specifically IPm, IPs, pЄq, and pЄqs (see Table 1)
n = number of samples

NICKEL

Nickel, like chromium, is a potential contaminant at several SNL environmental restoration sites. Nine samples of Tijeras Greenstone (Table 3; Appendix D) from 8 different locations were analyzed for nickel. The median nickel content of the samples is

51 ppm. The nickel content of the greenstone samples ranges from 40 to 92 ppm (Table 3, Appendix D).

DISCUSSION

The number of samples collected and analyzed for each rock type was small, thus, a detailed statistical analysis of the various data sets was not attempted. Nonetheless, the study provided much new information about the chromium and major-element content of KAFB-area rocks.

CHROMIUM

Chromium metal is won only from the mineral chromite ($FeCr_2O_4$). All known major deposits of chromite have crystallized from mafic or ultramafic magmas (Evans, 1980). Chromite is not common in greenstone belts, except for Selukwe in Zimbabwe-Rhodesia. Ninety-eight percent of the world's chromium reserves are in the Republic of South Africa and Zimbabwe-Rhodesia. The only other countries with known significant reserves are the former Soviet Union, Turkey, Greenland, and Canada (Evans, 1980).

The mean crustal abundance of chromium is 100 ppm (Evans, 1980). Condie (1980) listed average chromium concentrations of 300, 490, and 900 ppm for mid-ocean ridge basalt, depleted Archean tholeiite, and basaltic komatiite, respectively. As shown by the data in Table 3 of this report, greenstone samples from all but two locations in the KAFB area had lower chromium contents compared to those typical of mid-ocean ridge basalts and other mafic rocks.

KAFB-area rocks, other than greenstone, contain low to about average levels of chromium (Table 3, Appendix D) compared to the mean crustal abundance of 100 ppm. We speculate that much of the chromium contained in the quartzite-schist and siltstone samples is substituting for iron, which occurs at moderate concentrations in both of these rock types. All but one of the quartzite-schist and siltstone samples have chromium contents that are lower than the average crustal abundance of 100 ppm.

Biotite is a major constituent of both the biotite-granite and the Sandia Granite. Other investigators have proposed that high chromium contents could be associated with biotite in these rocks. However, chromium concentrations (Table 3, Appendix D) are low in these granites ($\leq$ 12 ppm), and are much less than 100 ppm.

Horn and Adams (1966) reported an average chromium concentration of 198 ppm for igneous rocks. Except for five greenstone samples collected at three locations, all igneous rock samples collected for this study had chromium contents lower than 198 ppm.

MAJOR-ELEMENT CONTENT

Typical major-element compositions for ultramafic rocks, gabbro, andesite, granodiorite, and granite are summarized in Table 5 from Nockolds and others (1978). Major-element compositions of the 13 greenstone samples are typical of gabbro, as shown by their relatively low SiO_2 and K_2O concentrations, and their relatively high Fe_2O_3-T, MgO, and CaO contents (Table 5, Appendix D). None of the 13 greenstone samples was found to exhibit an ultramafic composition.

Table 5
Typical Major-Element Compositions of Ultramafic Rocks, Gabbro, Andesite, Granodiorite, and Granite
(in weight percent)

Element (Oxide)	Ultramafic Rocks	Gabbro	Andesite	Granodiorite	Granite
SiO_2	42.0	48.36	54.90	66.88	70.41
TiO_2	1.1	1.32	1.02	0.57	0.45
Al_2O_3	5.7	16.84	17.73	15.66	14.38
Fe_2O_3	3.5	2.55	2.36	1.33	1.04
FeO	9.6	7.92	5.56	2.59	1.93
MnO	0.21	0.18	0.15	0.07	0.06
MgO	23.0	8.06	4.93	1.57	0.81
CaO	14.4	11.07	7.88	3.56	1.97
Na_2O	0.8	2.26	3.70	3.84	3.23
K_2O	0.5	0.56	1.11	3.07	4.95
P_2O_5	0.2	0.24	0.26	0.21	0.20

Note
All listed compositions are from Nockolds and others (1978)
Ultramafic rocks - median value for average dunite, peridotite, pyroxenite, and hornblendite
Gabbro - average of 160 samples
Andesite - average of 50 samples
Granodiorite- average of 137 samples
Granite - average of 166 samples

As noted previously, samples g8, g10, and g11 were collected from the same outcrop. Although an effort was made to avoid contamination of the rock samples, quartz veins occur commonly throughout the greenstone mass of this particular outcrop. The quartz veins and associated silicic alteration probably caused the SiO_2 contents of these samples (Table 3, Appendix D) to be elevated above the typical SiO_2 value for gabbro (48.36 wt%, Table 5).

SiO_2 contents of KAFB-area rocks are highest for the quartzite samples (q1 and q2), which is not surprising given that they were composed almost exclusively of quartz grains cemented by silica. Samples of biotite granite, Sandia Granite, and metarhyolite contain relatively high SiO_2 and K_2O, and relatively low CaO, MgO, and Fe_2O_3-T, as compared to typical samples of Tijeras Greenstone and gabbro (Tables 3 and 5). Major-element compositions of the two granites and the metarhyolite are typical of silicic igneous rocks (Table 5).

Moderately high K_2O contents of the quartzite-schist samples (Table 3, Appendix D) likely reflect their sericite content. The siltstone samples from the Sandia Formation and the Los Moyos Limestone also contain relatively high K_2O (Table 3, Appendix D), probably due to constituent clay minerals and grains of potassium feldspar.

NICKEL

Economic nickel is produced from nickeliferous laterites (derived from peridotites) and nickel sulphide ores. All known nickel sulfide deposits are associated with mafic or ultramafic rocks (Evans, 1980). Condie (1980) reported average nickel contents of 100, 140, and 390 ppm for mid-ocean ridge basalt, depleted Archean tholeiite, and for basaltic komatiite, respectively. The average crustal abundance of nickel is 70 ppm (Evans, 1980).

As previously noted by Condie (1980), the Tijeras Greenstone contains relatively low concentrations of nickel compared to mid-ocean ridge basalt and other mafic volcanics.

CONCLUSIONS

The highest chromium concentrations for KAFB-area rocks are found in the Tijeras Greenstone. The median chromium content of the Tijeras Greenstone is 130 ppm; the first and third quartiles are 77 and 361 ppm, respectively. In contrast, none of the other KAFB-area rock types has a chromium content greater than 130 ppm, and only two samples have values exceeding 77 ppm.

Surface exposures of the Tijeras Greenstone are limited to only a small portion of the KAFB area. Therefore, detritus derived from the greenstone belt generally constitutes only a small fraction of KAFB-area sediments. Where little or no greenstone detritus is present, alluvial sediments derived from KAFB-area source rocks are unlikely to contain concentrations of chromium that significantly exceed 100 ppm (by XRF methods). Furthermore, because the majority of KAFB-area rocks contain little chromium, it follows that significant physical concentration of chromium-bearing minerals is unlikely to occur due to sedimentary processes. Thus, other sources of chromium must be found to explain the elevated values found at some SNL environmental restoration sites.

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APPENDIX A

Compositions of KAFB-area Rocks, Phase 1

Note: See Table 1 for key to sample abbreviations.

SAMPLES

	a1	bg1	bg2	g6	gs	gs2
SiO_2	64.4	71.1	68.1	50.3	68.7	67.1
TiO_2	0.76	0.40	0.40	1.29	0.82	1.15
Al_2O_3	15.1	14.5	15.4	11.4	13.1	12.6
Fe_2O_3-T	6.83	2.80	2.42	14.4	4.85	5.67
MgO	2.77	0.37	1.12	9.12	1.15	1.63
CaO	3.49	1.52	1.86	7.18	2.57	2.82
MnO	0.09	0.09	0.05	0.29	0.09	0.12
Na_2O	1.53	3.05	3.55	1.73	3.48	3.86
K_2O	1.72	4.22	3.98	0.62	4.00	3.59
P_2O_5	0.16	0.09	0.14	0.11	0.37	0.53
S	0.011	0.008	0.047	0.017	0.013	0.009
LOI	2.82	1.14	2.02	1.92	1.18	1.31
Total	99.681	99.288	99.087	98.377	100.323	100.389
Cr	69	12	4	<3	<3	<3

	mr1	mr2	q1	g7	g8	g9
SiO_2	72.4	71.3	97.4	50.4	71.1	54.1
TiO_2	0.36	0.44	0.06	0.70	0.16	0.78
Al_2O_3	14.1	13.8	0.88	10.8	7.74	12.1
Fe_2O_3-T	2.39	2.73	0.37	12.3	8.21	12.1
MgO	0.55	0.68	0.13	14.3	4.84	8.71
CaO	1.68	1.85	0.11	6.99	5.42	7.89
MnO	0.07	0.07	<0.01	0.24	0.16	0.26
Na_2O	3.38	3.23	0.17	1.91	0.04	2.88
K_2O	4.47	4.28	0.21	0.08	0.15	0.28
P_2O_5	0.13	0.18	0.04	0.02	0.08	0.09
S	0.007	0.01	0.014	0.008	0.022	0.019
LOI	0.87	0.89	0.14	2.42	2.22	2.25
Total	100.407	99.46	99.524	100.168	100.142	101.459
Cr	<3	<3	3	84	562	51

Major elements are in weight percent.
Cr is in parts-per-million (ppm).
Fe_2O_3-T is total iron expressed as Fe_2O_3.
LOI is loss on ignition.

SAMPLES

	qs1	qs2	l1	s1	s2
SiO_2	52.2	64.4	63.0	47.0	73.5
TiO_2	0.85	0.73	0.69	0.62	0.32
Al_2O_3	25.5	20.6	17.6	14.4	8.50
Fe_2O_3-T	6.87	4.26	5.59	11.6	3.08
MgO	0.78	0.43	3.91	1.85	1.38
CaO	0.21	0.10	0.68	3.77	4.87
MnO	0.02	0.05	0.01	0.01	0.03
Na_2O	2.21	0.50	0.79	0.31	0.20
K_2O	5.22	5.06	3.32	2.47	1.20
P_2O_5	0.06	0.04	0.06	0.10	0.14
S	0.009	0.009	0.03	0.46	0.014
LOI	4.15	2.47	4.19	15.94	7.89
Total	98.079	98.649	99.87	98.53	101.124
Cr	74	69	62	108	80

Major elements are in weight percent.
Cr is in parts-per-million (ppm).
Fe_2O_3-T is total iron expressed as Fe_2O_3.
LOI is loss on ignition.

APPENDIX B

Compositions of KAFB-area Rocks, Phase 2

Note: See Table 2 for key to sample abbreviations.

SAMPLES

	g10	g11	g12(a)	g12(b)	g12(c)	g13	q2
SiO_2	62.1	65.6	55.4	55.5	56.0	50.2	98.0
TiO_2	0.17	0.18	0.22	0.22	0.23	0.79	0.06
Al_2O_3	9.55	10.4	15.1	15.1	15.2	14.2	0.50
Fe_2O_3-T	10.5	8.47	11.2	11.2	11.2	11.9	0.07
MgO	5.37	4.66	6.25	6.21	6.63	8.32	0.08
CaO	8.56	7.22	5.49	5.51	5.56	8.32	0.04
K_2O	0.01	0.63	0.19	0.18	0.19	0.40	0.11
Na_2O	<0.01	<0.01	1.58	1.60	1.58	2.78	<0.01
MnO	0.17	0.13	0.08	0.08	0.08	0.23	<0.01
P_2O_5	0.04	0.04	<0.01	<0.01	<0.01	0.04	<0.01
LOI	2.10	2.22	3.68	3.68	3.68	2.42	0.17
Total	98.57	99.55	99.19	99.28	100.35	99.6	99.03

	g10 CM1	g10 CM2	g10 CM3	g11	g12	g13	q2
Nb	3	3	3	4	2	4	15
Zr	23	22	22	26	16	43	40
Y	6	6	6	8	6	21	4
Sr	59	59	60	84	168	114	8
Rb	<6	<6	<6	22	7	19	6
Th	<2	<2	<2	2	<2	2	<2
Pb	6	3	4	8	3	5	3
Ga	9	9	9	9	13	16	<2
Zn	113	112	119	97	99	103	<1
Cu	29	31	31	28	56	61	2
Ni	64	65	64	51	42	92	4
Cr	603	616	597	361	222	162	5
V	187	189	182	106	281	314	2
Ba	207	207	219	421	298	119	21

Major elements are in weight percent.
Trace elements are in parts-per-million (ppm).
Fe_2O_3-T is total iron expressed as Fe_2O_3.
LOI is loss on ignition.
CM1 through CM3 are triplicate analyses of g10.
g12(a) through g12(c) are triplicate analyses of g12

APPENDIX C

Composition of the Tijeras Greenstone (Condie, 1980)

Note: See Figure 2 for sample locations.

SAMPLES

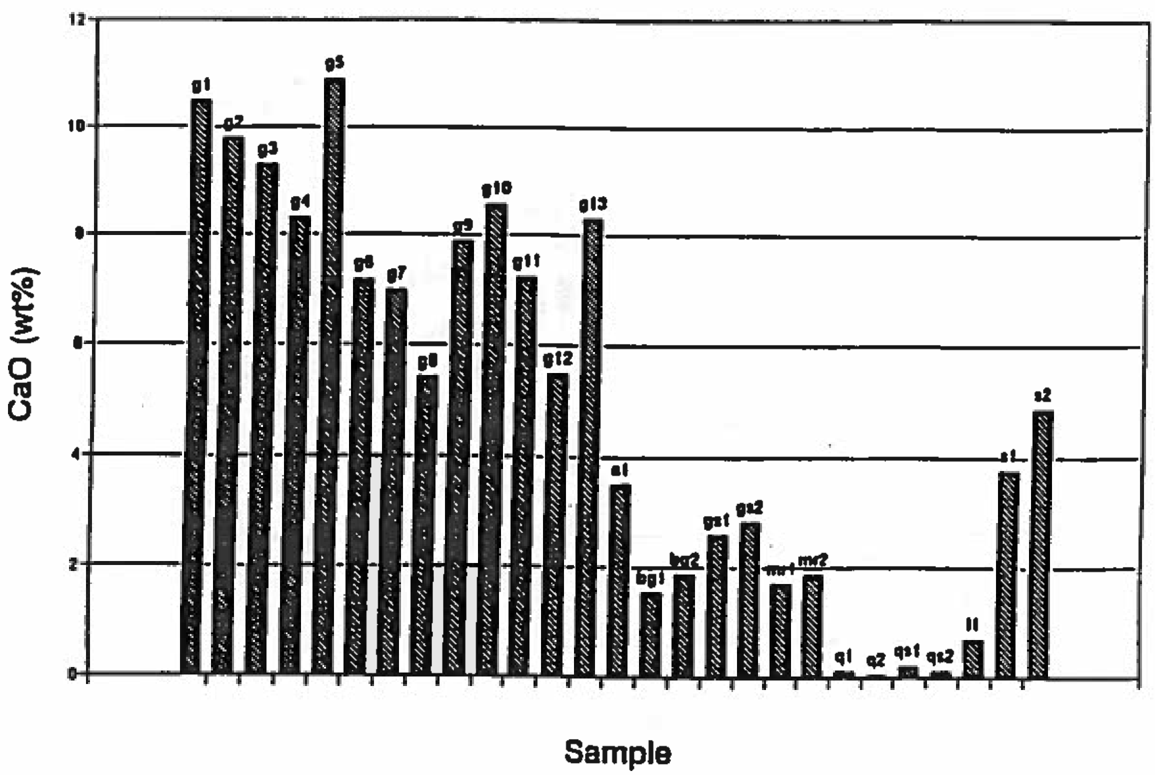
	g1	g2	g3	g4	g5
SiO_2	48.2	50.2	50.9	49.5	49.6
TiO_2	0.82	0.92	0.76	0.94	0.99
Al_2O_3	12.8	12.2	11.1	11.4	11.7
Fe_2O_3-T	13.5	14.7	14.4	15.1	13.9
MgO	10.6	6.96	8.44	8.80	8.65
CaO	10.5	9.75	9.27	8.30	10.9
Na_2O	1.36	2.36	2.94	3.32	2.10
K_2O	0.25	0.58	0.23	0.23	0.36
H_2O	1.71	1.98	1.83	2.14	1.82
CO_2	0.01	0.13	<0.01	0.21	<0.01
Total	99.75	99.98	99.88	99.94	100.02
Pb	14	9.1	11	12	20
Zn	80	91	86	102	138
Cu	73	76	71	82	42
Ni	69	40	49	47	74
Cr	381	85	77	73	130
Co	56	54	54	51	59
Zr	140	139	184	214	210
Ba	42	157	28	83	150
Rb	12	40	8	2	2
Sr	121	116	123	86	135
Th	0.65	0.39	0.11	1.2	0.18
Y	34	40	37	41	43
La	2.7	3.1	1.1	2.0	1.3
Ce	5.6	9.8	4.2	7.0	4.6
Sm	2.2	2.4	2.0	2.0	1.9
Eu	0.83	0.95	0.89	0.72	0.73
Tb	0.49	0.62	0.70	0.57	0.60
Yb	2.0	2.8	2.4	2.7	2.8
Lu	0.38	0.47	0.42	0.48	0.50

Major elements are reported as oxides (wt%).
Trace constituents are reported in parts-per-million (ppm).

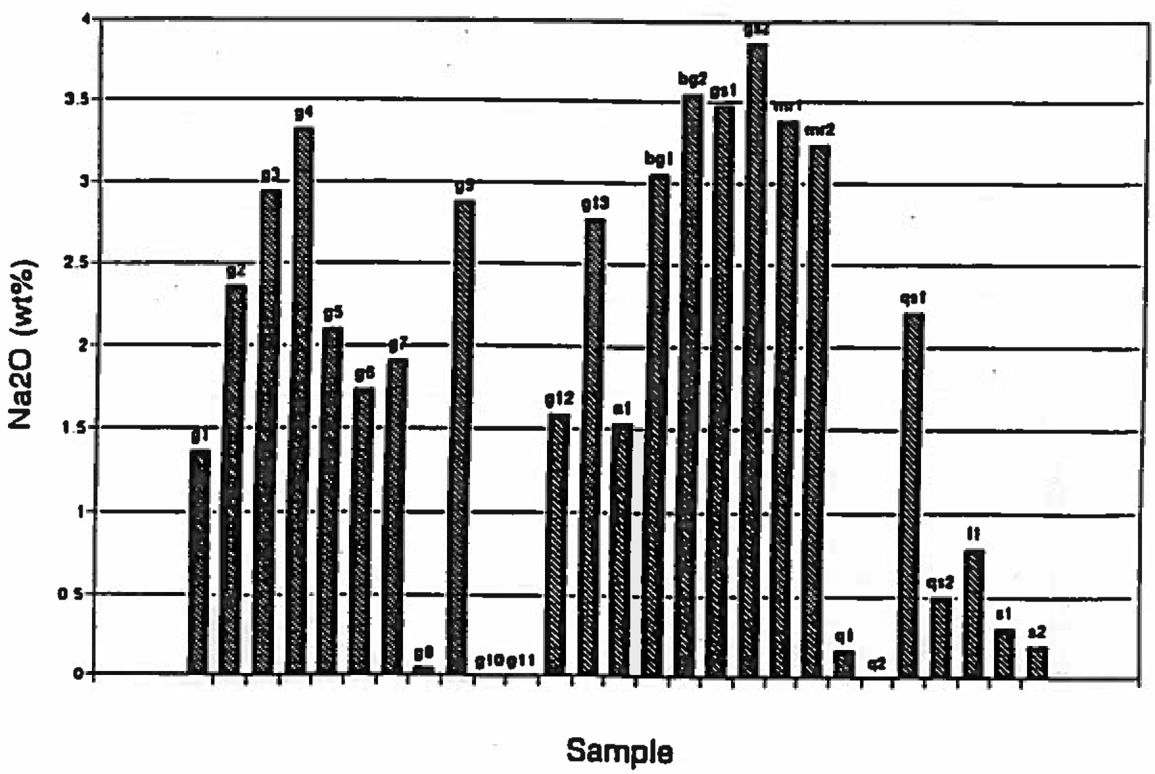
APPENDIX D

Bar Graphs Showing Major-Element, Chromium, and Nickel Contents of KAFB-Area Rocks

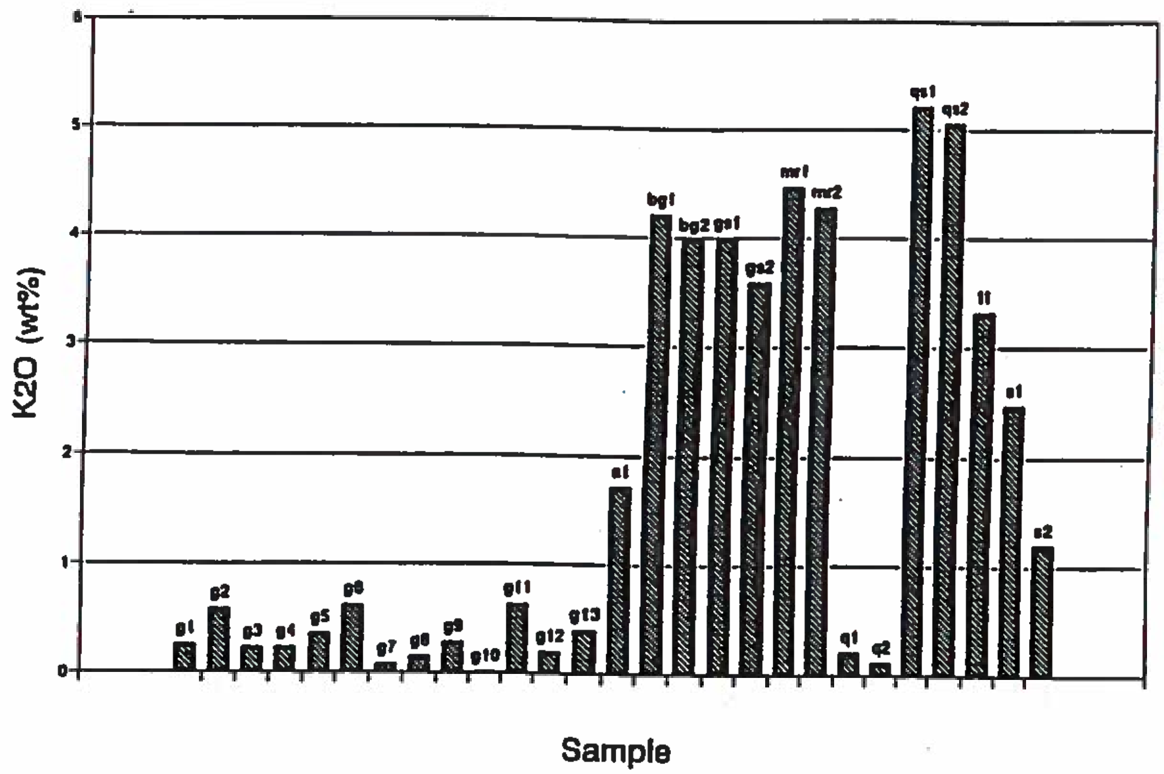
Notes: See Table 3 for key to sample abbreviations. Values plotted at zero (0) represent concentrations below respective detection limits (except for nickel, where 0 means the sample was not analyzed for this constituent). See Appendices A-C for specific values.

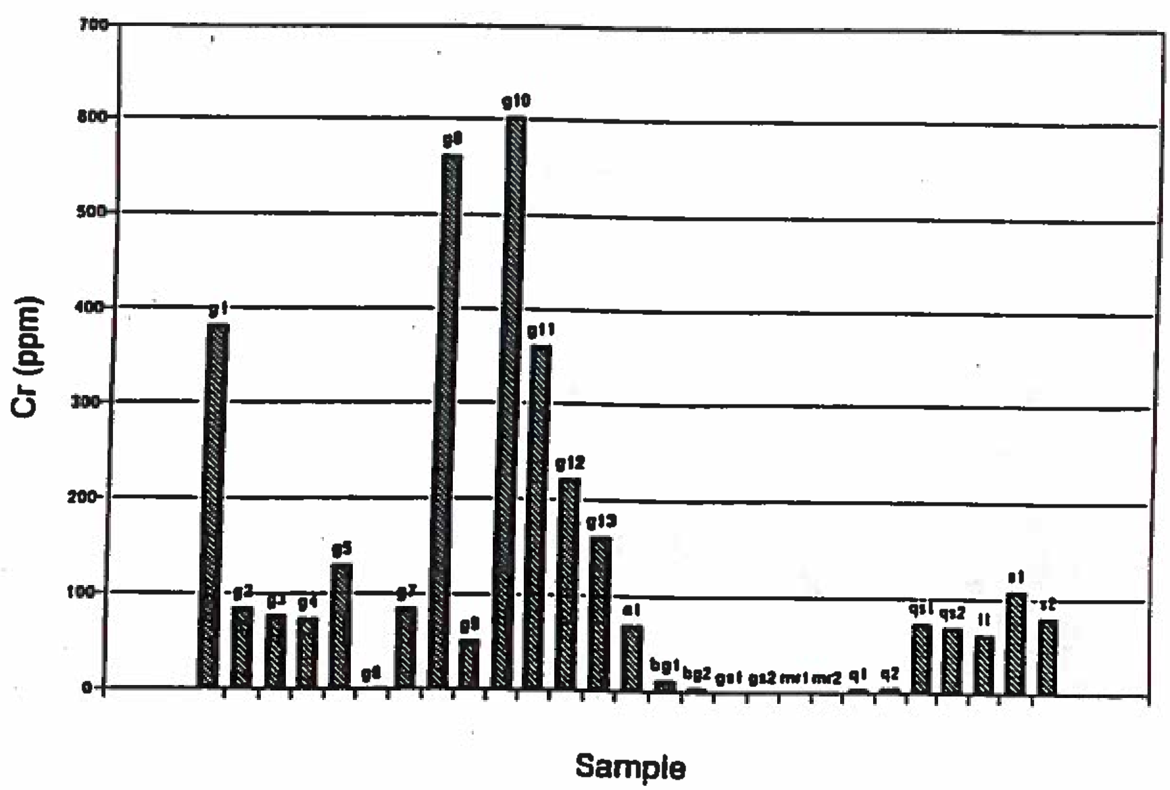


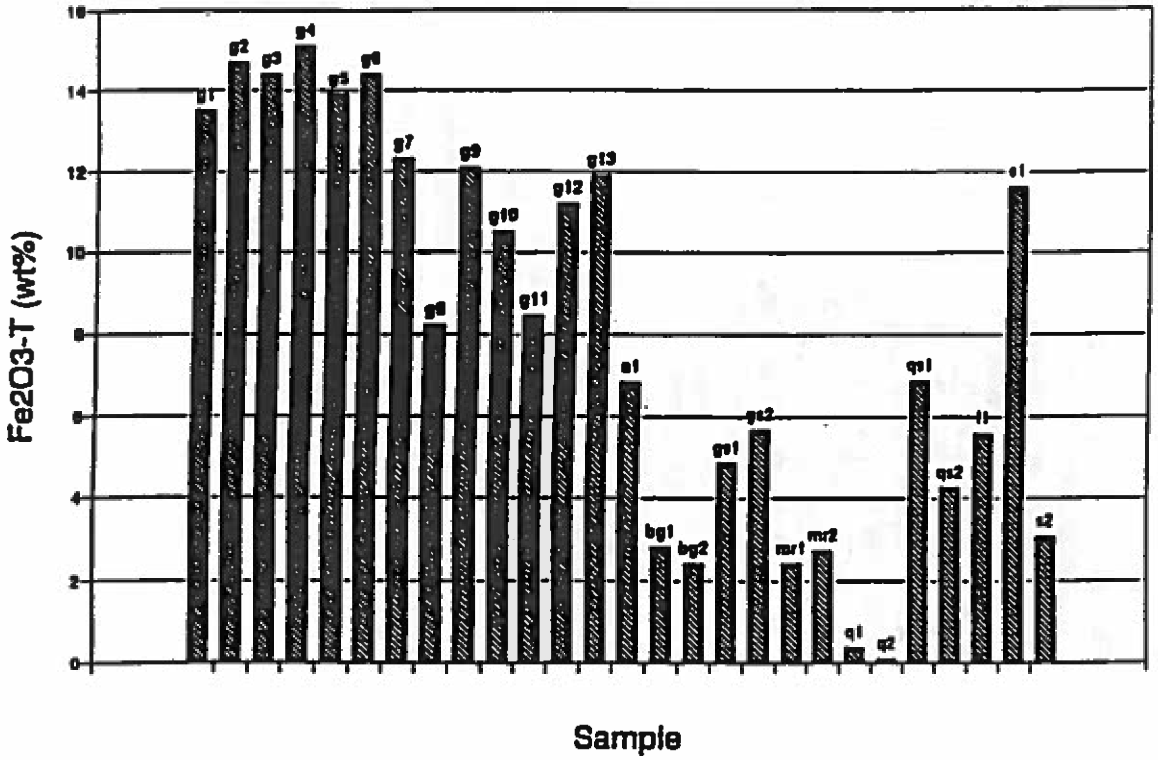
CaO (wt%)
Sample
g1
g2
g3
g4
g5
g6
g7
g8
g9
g10
g11
g12
g13
s1
bg1
bg2
gs1
gs2
mr1
mr2
q1
q2
qs1
qs2
l1
s1
s2



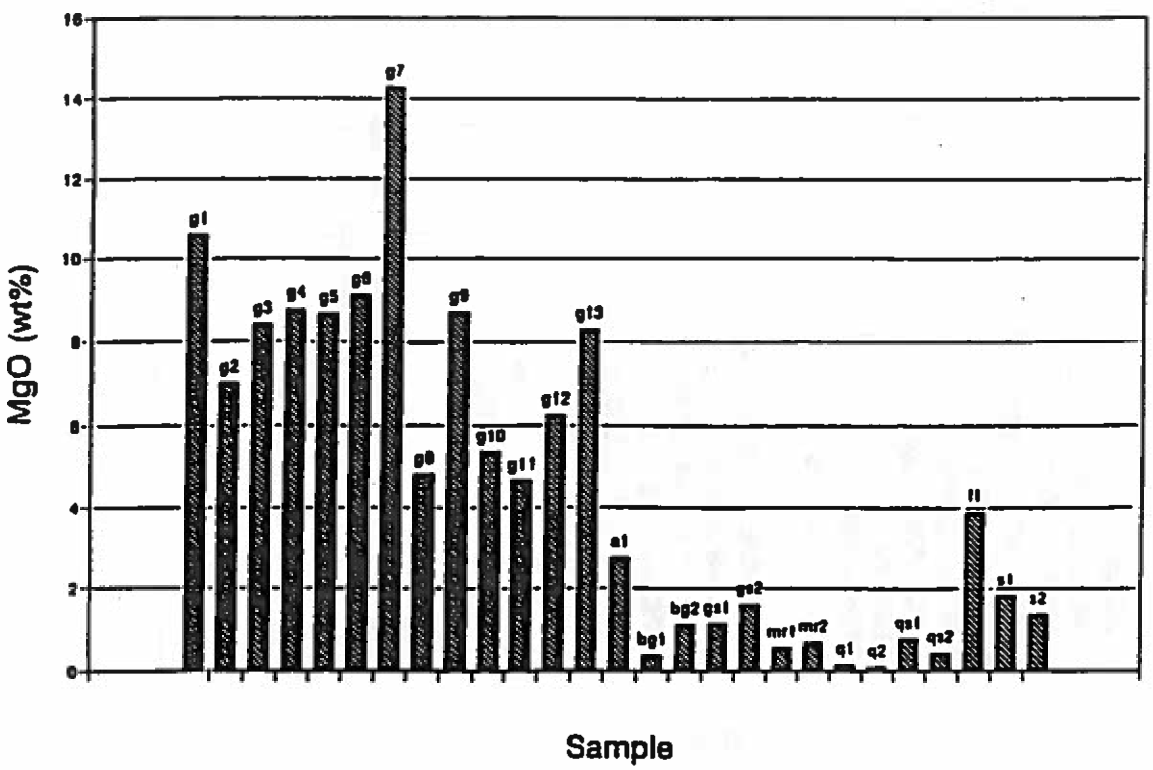
Na2O (wt%)
Sample
g1
g2
g3
g4
g5
g6
g7
g8
g9
g10
g11
g12
g13
s1
bg1
bg2
gs1
gs2
mr1
mr2
q1
q2
qs1
qs2
l1
s1
s2


K2O (wt%)
Sample
g1
g2
g3
g4
g5
g6
g7
g8
g9
g10
g11
g12
g13
a1
bg1
bg2
gs1
gs2
mr1
mr2
q1
q2
qs1
qs2
l1
s1
s2

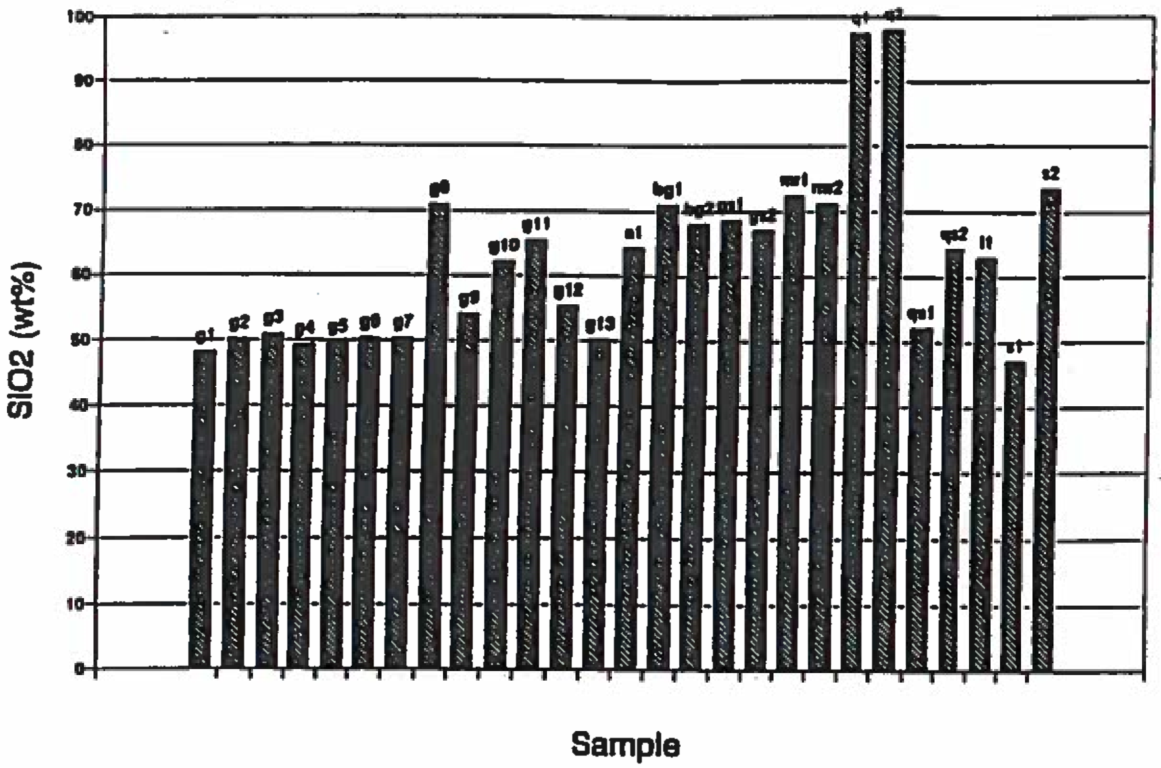

Cr (ppm)
Sample
g1
g2
g3
g4
g5
g6
g7
g8
g9
g10
g11
g12
g13
a1
bg1
bg2
gs1
gs2
mr1
mr2
q1
q2
qs1
qs2
l1
s1
s2



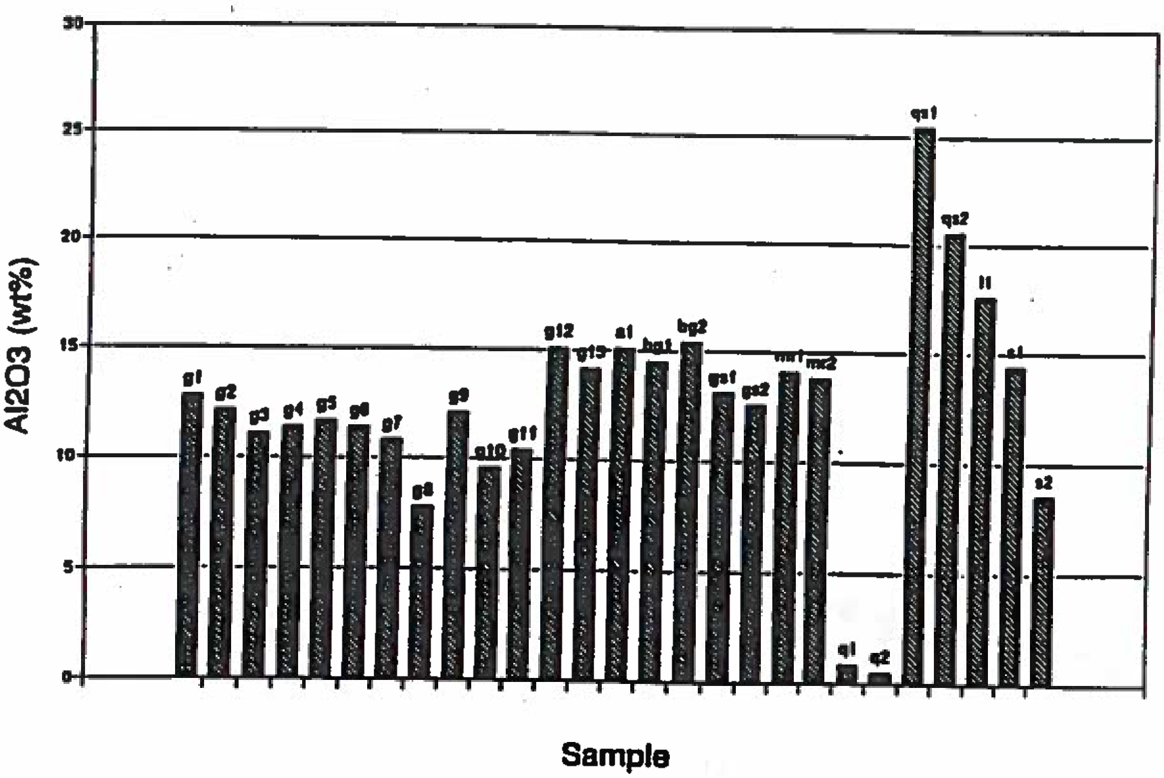
Fe2O3-T (wt%)
Sample



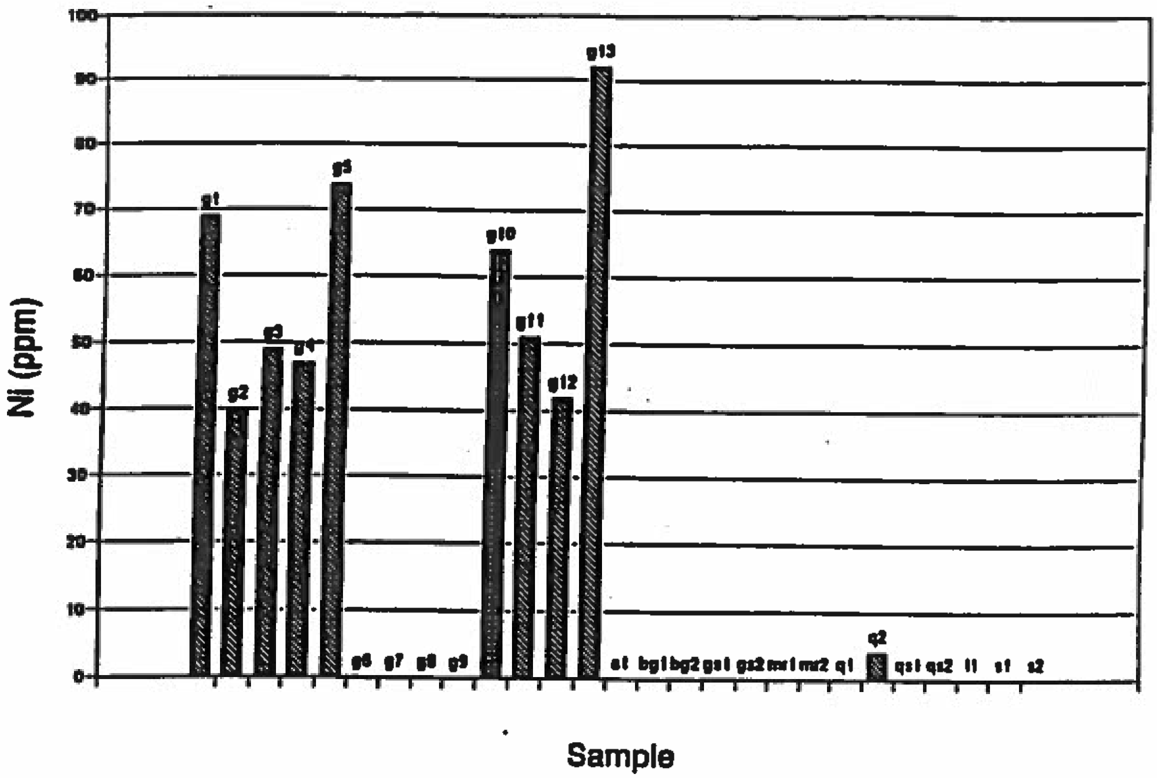
MgO (wt%)
Sample



SiO2 (wt%)
Sample



Al2O3 (wt%)
Sample



Ni (ppm)
0
10
20
30
40
50
60
70
80
90
100
g1
g2
g3
g4
g5
g6
g7
g8
g9
g10
g11
g12
g13
bg1
bg2
q1
q2
qs1
qs2
s1
s2
Sample