GJPO–WMP–96

Geochemical Study of Groundwater at Sandia National Laboratories/New Mexico and Kirtland Air Force Base

October 1995

MASTER

U.S. Department of Energy
Grand Junction Projects Office

Work Performed Under DOE Contract No. DE–AC04–94AL96907 for the U.S. Department of Energy

GJPO-WMP-96

Geochemical Study of Groundwater at Sandia National Laboratories/New Mexico and Kirtland Air Force Base

October 1995

DISCLAIMER

Prepared by Rust Geotech
U.S. Department of Energy
Albuquerque Operations Office
Grand Junction Projects Office
Grand Junction, Colorado
Under DOE contract No. DE-AC04-94AL96907

Contents

Page

Contents (Continued)

Tables

Figures

Page

Executive Summary

Sandia National Laboratories/New Mexico (Sandia/NM) requested that the U.S. Department of Energy (DOE) Grand Junction Projects Office (GJPO), through its prime contractor, Rust Geotech, provide interpretation of groundwater geochemical data at Sandia/Kirtland Air Force Base (KAFB).

Existing analytical data were used to prepare a database with relevant chemical analyses for groundwater samples collected at the two sites. A subset of the database was selected that contains one set of chemical analyses for each sampling location (well or spring). These data were selected primarily on the basis of charge balance. Piper diagrams, Stiff diagrams, histograms, and spatial plots were used to display and analyze these geochemical data. Geochemical modeling using NETPATH and PHREEQE was used to help interpret observed trends.

Chemical similarities between groundwaters at Coyote Springs and EOD Hill suggest a common origin. Both groundwaters are elevated in ionic strength, Cl, TIC, Na, Ca, K, and Mg. A reaction-path model driven by CO_2 loss provides a thermodynamically valid explanation for the evolution of these fault-related groundwaters. Stable isotopes of D/H and $^{18}O/^{16}O$ support this reaction-path model.

Groundwater in the Santa Fe Group in the basin away from the boundary faults is dominated by a dilute component. Only minor chemical interactions between pure water and mineral phases are required to produce this dilute water. A more saline fluid upwells along the basin-boundary faults and mixes with the dilute groundwater.

Based on geochemical modeling, the chemical composition of the Santa Fe Group groundwater in the South Fence Road wells can be explained by mixing of dilute groundwater with saline groundwater upwelling along basin-boundary faults. Approximately 62 percent of the dilute Santa Fe Group water must mix with 36 percent of a saline water similar in chemical composition to EOD Hill. An additional 2 percent of SO_4-rich groundwater such as that present in SFR–3T is needed to balance the SO_4.

The chemistry of the groundwater in the footwall (Lower Tertiary unit) of the fault along South Fence Road is explained by interaction with gypsum and Na-rich exchangeable clays. Groundwater in the vicinity of the SFR–3T well is in contact with gypsum, as indicated by the near-zero saturation index. This water, which is high in Ca and SO_4, flows away from gypsiferous beds in the Yeso Formation and in the fault and contacts Na-rich clays. Ca is exchanged for Na to produce the high-Na and high-SO_4 groundwater sampled in the SFR–4T well. A small component (<2%) of this high-SO_4 water mixes with the groundwater in the Santa Fe Group to produce slightly elevated SO_4 concentrations near the faults.

A nitrate-plus-nitrite anomaly beneath the Tijeras Golf Course indicates vertical infiltration to greater than 400 feet. This local phenomena is due to the high infiltration of irrigation water containing nitrogen-based fertilizer. Mass-balance modeling shows that relatively pure infiltration water reacting with small amounts of calcite, gypsum, halite, and clays could produce this groundwater.

Although the modeling study is useful in characterizing and understanding the nature of chemical reactions occurring at the site, definitive conclusions about flow paths are illusive. The scarcity of mineralogical information restricts our ability to place constraints on the models. Collection of the large amount of subsurface data needed to model flow paths uniquely is impractical. It is recommended that more cost-effective information on flow paths would be generated by completing additional wells and by using environmental tracers such as ^{3}H, ^{36}Cl, and ^{14}C.

1.0 Introduction

The U.S. Department of Energy (DOE) Grand Junction Projects Office (GJPO) and its contractor, Rust Geotech, support the Kirtland Area Office by assisting Sandia National Laboratories/New Mexico (Sandia/NM) with remedial action, remedial design, and technical support of its Environmental Restoration Program. To aid in determining groundwater origins and flow paths, the GJPO was tasked to provide interpretation of groundwater geochemical data.

The purpose of this investigation was to describe and analyze the groundwater geochemistry of the Sandia/NM Kirtland Air Force Base (KAFB). Interpretations of groundwater origins are made by using these data and the results of "mass balance" and "reaction path" modeling. Additional maps and plots were compiled.to more fully comprehend the geochemical distributions. A more complete set of these data representations are provided in the appendices. Previous interpretations of groundwater-flow paths that were based on well-head, geologic, and geochemical data are presented in various reports (Sandia/NM 1993, 1994, 1995) and were used as the basis for developing the models presented in this investigation.

A thorough understanding of groundwater flow directions and recharge areas is needed to make reliable predictions of the direction and extent of contaminant transport. Geochemical modeling is a tool that aids in this understanding. An understanding of the chemical reactions that are occurring in the aquifer is also needed to make reliable predictions of the chemical retardation of the contaminants (retardation assessment was not part of this study). Geochemical modeling of field sites seldom produces a unique solution to the question of groundwater origin. Geochemical simulations can, however, be used to constrain conceptual groundwater flow models.

The main objectives of this study were (1) to present key groundwater chemistry from the Sandia/KAFB Site-Wide Hydrogeologic Characterization Project in a form that can be readily retrieved and used in interpretive studies and (2) to test the validity of various interpretations of groundwater flow paths and the location of recharge areas by using geochemical spatial relationships and reaction path methodologies. These objectives were met by preparing a set of graphical data representations, including spatial chemical plots, histograms, Piper diagrams, and Stiff diagrams. These data representations were then used to develop conceptual groundwater chemistry models that were tested against mass balance and thermodynamic constraints.

2.0 Geochemical Data Used in This Study

Groundwater chemistry data used for this study include data from the Sandia/ER Project and the Sandia/NM Groundwater Protection Program. These sites were sampled regularly by the ER Project and the Groundwater Surveillance Task of the Groundwater Protection Program. Well data are provided in Table 2-1. Other groundwater data are available for the site, but these data are typically analyses of water samples from wells concentrated in specific waste-site areas that have not been routinely sampled for the purpose of defining major-ion chemistry. Analyses used in this study include major cations (Ca, Na, K, Mg); major anions (SO_4, Cl), field alkalinity (used to compute bicarbonate [HCO_3]) and pH, nitrate [NO_3] or nitrate plus nitrite (NPN); and natural tracers; bromide (Br); fluoride (F).

Data from the 1992 (two samplings), 1993 (four samplings), and 1994 (three samplings) field seasons were used in this study. Almost all the wells numbered 1 through 13 and 18 and 19 (Table 2-1) and all the springs were sampled during these three sampling periods. Wells SFR-1D, SFR-2S, SFR-3P, and SFR-3T were not sampled in 1992. Data for wells 20 through 24 were available only for the 1995 sampling season (data provided by F. Lauffer). Data for wells 1 through 19 and the springs are in Sandia/NM (1993, 1994a, 1995).

2.1 Selection of the Most Representative Data from the 12 Sampling Periods

Because interpretation of groundwater origins involves determining the spatial variation of groundwater chemistry, the selection of a single set of chemical parameter values were necessary to represent each sampling location. Groundwater data from the 12 sampling periods were examined to determine if any chemical parameters varied systematically over time. No systematic variations were apparent. A set of data comprising a single set of chemical values was selected for each sampling location. This data compilation is called the most representative data (MRD). These MRD were selected from the best available data as determined by charge balance calculations.

Sampling data that lacked values for Ca, Na, K, Mg, SO_4, Cl, pH, or alkalinity were rejected for use in the MRD. Because dissolved carbon dioxide (CO_2) will exchange with the atmosphere, pH and alkalinity measurements are reliable indicators of subsurface conditions only if these measurements are made immediately after sampling. Therefore, samplings that did not include field measurements of pH and alkalinity were not used in the MRD. If any analyses of Ca, Na, K, Mg, SO_4, Cl, pH, or alkalinity were "suspect," data from that sampling period were not used in the MRD. "Suspect data" are those data that have a significant deviation from typical values, as indicated by comparison with data from other sampling periods. "Suspect" data were identified based solely on the judgement that these analytical values are unlikely to be real; likely they are due to reporting errors or equipment malfunctions. No data were eliminated based on statistical outlier analysis. Because wells MRN-2 and PL-1 had high turbidity and

Table 2-1. Well Information[a]

Well No.	Well Name	Well Depth (feet)	Depth to Water (feet)	Screened Interval (feet)	Formation Sampled/Geologic Unit[b]
1	Burn Site Well	350	68[d]	231-341	pЄ$_{sg}$
2	CWL-BW2	998	499[c]	490-980	Tsf
3	EOD Hill	212	144[c]	204-212	IPm
4	Golf Course South	495	315[c]	437-457	Tsf
5	Greystone	57	53[c]	44-54	Qal
6	KAFB-10	1050	496[c]	495-814	Tsf
7	LF/DM-01	480	457[c]	415-465	Tsf
8	LF/DM-02	450	404[c]	378-428	Tsf
9	MVMW-J	225	216[c]	200-220	Tsf
10	MVMW-K	300	290[c]	275-295	Tsf
11	MWL-BW1	519	465[c]	452-472	Tsf
12	NW-TA3	461	449[c]	435-455	Tsf
13	Schoolhouse	107	95[c]	83-103	Qal and pЄ
14	SFR-1D	510	92[d]	348-368	Tsf
15	SFR-2S	365	101[d]	97-117	Tsf
16	SFR-3P	914	164[c]	175-195	Tsf
17	SFR-3T	1154	92[d]	713-733	Tℓ
18	SW-TA3	467	426[c]	407-427	Tsf
19	Tijeras East	571	478[c]	465-527	Tsf
20	SFR-4T	377	294[d]	340-360	Tℓ
21	PL-3	480	452[e]	445-465	Tsf
22	TRN-1	510	82[d]	320-340	Pa
23	MRN-2	455	414[d]	410-440	Tsf
24	TJA-2	310	274[d]	275-295	Tsf

[a] Data provided by W. Foutz (Sandia/NM).

[b] Geologic units: pЄ = Precambrian basement; s = schist; and g = granite.
Formations: Qal = Quaternary alluvium; Tsf = Tertiary Santa Fe Group; Tℓ = Lower Tertiary (pre-Tsf); Pa = Permian Abo Formation; and IPm = Madera Formation (limestone).

[c] Depth to water measured December 1994.

[d] Depth to water from well completion records.

[e] No depth to water reported for PL-3, this value is from PL-2 drilled 5 feet away.

were located close to other wells, they were not included in this study. Although Hubbel Springs has somewhat erratic pH values and KAFB-10 potentially has problematic analyses for alkalinity, Cl, and pH, these sampling sites were included for comparison purposes.

The analyses rejected because of lack of data or "suspect data" are listed in Table 2-2.

Table 2-2. Rejected Data

Sampling Location	Sampling Date	Reason for Rejection
Burn Site	July 1993	Low SO_4
Burn Site	April 1993	Low Mg
Coyote Springs	March 1994	No field alkalinity
Coyote Springs	September 1993	Low Mg
Coyote Springs	December 1993	Low Na
Coyote Springs	July 1993	Low SO_4
Coyote Springs	July 1992	Low alkalinity
CWL-BW2	April 1993	Low Cl
EOD Hill Well	July 1992	Low Ca
Golf Course South	June 1994	No field alkalinity
Golf Course South	July 1993	No field alkalinity
Golf Course South	April 1993	High K
Golf Course South	January 1992	Low pH, Low Ca
Greystone	March 1994	Low SO_4
Greystone	July 1993	No field alkalinity
Hubbell Spring	September 1994	High field alkalinity
KAFB-10	March 1994	No field alkalinity
KAFB-10	April 1993	No field alkalinity
LF/DM-1	July 1993	Low field alkalinity
LF/DM-2	July 1993	High field alkalinity
LF/DM-2	April 1993	High Ca
MVMW-J	July 1993	Low pH
MVMW-K	March 1994	No field alkalinity
MVMW-K	January 1992	High Cl
MWL-BW1	March 1994	No field alkalinity
NW-TA3	July 1993	No field alkalinity
NW-TA3	April 1993	High Cl
Schoolhouse	March 1994	Low Cl

Table 2-2 (continued). Rejected Data

Sampling Location	Sampling Date	Reason for Rejection
Schoolhouse	July 1992	Low Cl
Sol se Mete Spring	March 1994	No field alkalinity
Sol se Mete Spring	December 1993	No field alkalinity
Sol se Mete Spring	July 1993	No field pH
Sol se Mete Spring	April 1993	Low field pH
SFR-1D	July 1993	No field alkalinity
SFR-2S	July 1993	No field alkalinity
SW-TA3 Well	July 1993	Low pH
SW-TA3 Well	April 1993	High pH
Tijeras East	August 1992	Low SO_4
MRN-1	April 1995	High turbidity
PL-2	April 1995	High turbidity

Major cation, major anion, and pH data were used to compute the equilibrium ion distributions and mineral saturation indices for each groundwater sample with the program PHREEQE (Parkhurst et al. 1980). Table 2-3 lists the thermodynamic data used in this investigation.

Groundwater temperatures ranged from 7 to 24 °C but were generally between 15 and 20 °C. PHREEQE computations were performed at 25 °C, the standard temperature at which free energy data are reported. The small size of the temperature corrections would not affect the interpretations in this study.

The cation/anion ratios calculated by PHREEQE were used to select the MRD. Table 2-4 presents the cation/anion ratios calculated by PHREEQE for the data sets that remained after eliminating those that are based on lack of data or "suspect data."

Cation/anion ratios will approximate 1.0 if all chemical analyses are accurate and all significant components are included. Deviations from 1.0 indicate that these conditions are not met. Therefore, the MRD consists of the data set from each location that has a cation/anion ratio closest to 1.0. The MRD are listed in Table 2-5. The database containing the complete set of data is a text file named sand.dat and is included as Appendix A.

Table 2-3. Thermodynamic Data

Dissolved Species	Log K (25 °C)
$H_2O = OH^- + H^+$	-14.00
$CO_3^{2-} + H^+ = HCO_3^-$	10.33
$CO_3^{2-} + 2H^+ = CO_2^{\circ} + H_2O$	16.681
$SO_4^{2-} + H^+ = HSO_4^{2-}$	1.987
$Ca^{2+} + H_2O = CaOH^+ + H^+$	-12.598
$Ca^{2+} + CO_3^{2-} = CaCO_3^{\circ}$	3.153
$Ca^{2+} + CO_3^{2-} + H^+ = CaHCO_3^+$	11.345
$Ca^{2+} + SO_4^{2-} = CaSO_4^{\circ}$	2.309
$Mg^2 + H_2O = MgOH^+ + H^+$	-11.794
$Mg^{2+} + CO_3^{2-} = MgCO_4^{\circ}$	2.980
$Mg^{2+} + CO_3^{2-} + H^+ = MgHCO_3^+$	11.396
$Mg^{2+} + SO_4^{2-} = MgSO_4^{\circ}$	2.250
$Na^+ + CO_3^{2-} = NaCO_3^-$	1.268
$Na^+ + CO_3^{2-} + H^+ = NaHCO_3^{\circ}$	10.080
$Na^+ + SO_4^{2-} = NaSO_4^-$	0.700
$K^+ + SO_4^{2-} = KSO_4^-$	0.850
Minerals and Gases	
$H_2CO_3^{\circ} = CO_2$ (gas) $+ H_2O$	-1.466
$Ca^{2+} + CO_3^{2-} = CaCO_3$ (calcite)	-8.470
$Ca^{2+} + SO_4^{2-} + 2H_2O = CaSO_4^{\circ} \cdot 2H_2O$ (gypsum)	-4.602

2.2 Mineralogical Data

Mineralogic data are needed to constrain geochemical models that involve the interaction of groundwater with the solid grains of the aquifer. Mineralogic data available for this study are contained in lithologic logs of drill cores and cuttings. Detailed core logs were available for SFR-1D, SFR-2S, SFR-3P, SFR-3T, and SFR-4T. Logs without much mineralogic detail were available for Burn Site, CWL-BW2, EOD Hill, Golf Course South, KAFB-10, MVMW-J, MVMW-K, MWL-BW1, NW-TA3, and Tijeras East; no logs were available for the other wells. A summary of the mineralogy as compiled from these logs is provided in Appendix E.

Table 2-4. Parameters Calculated With PHREEQE

Sampling Location	Ionic Strength	Total Inorganic Carbon (mg/L)[a]	Cation/ Anion Ratio	Saturation Index		Log P_{CO_2} (atm)[b]
				Calcite	Gypsum	
Burn Site Well	0.014	69.10	1.03	-0.29	-1.264	-1.40
Coyote Springs	0.044	486.30	1.04	-0.05	-1.320	-0.17
CWL-BW2	0.017	113.78	1.02	0.06	-1.576	-1.22
EOD Hill Well	0.067	1175.20	1.00	0.39	-1.121	0.24
Golf Course South	0.009	32.22	1.31	-0.06	-1.694	-2.16
Greystone	0.014	99.72	1.05	0.06	-1.837	-1.35
Hubbell Spring	0.013	128.25	0.98	-0.98	-1.362	-0.76
KAFB-10	0.007	16.36	0.91	-0.55	-2.244	-2.69
LF/DM-01	0.004	23.87	1.01	0.07	-2.370	-2.86
LF/DM-02	0.008	45.60	1.04	0.05	-1.680	-2.04
MVMW-J	0.006	41.43	1.01	0.33	-2.239	-2.46
MVMW-K	0.006	40.62	0.97	0.66	-2.167	-2.79
MWL-BW1	0.009	59.18	1.12	0.24	-2.050	-2.09
NW-TA3	0.008	38.82	1.05	0.08	-1.748	-2.25
Schoolhouse	0.018	124.43	0.98	0.09	-1.656	-1.16
Sol se Mete Spring	0.01	58.66	1.05	0.27	-1.656	-1.92
SFR 1	0.019	145.08	1.01	0.07	-1.598	-1.03
SFR 2	0.016	103.01	0.99	-0.04	-1.611	-1.25
SFR 3P	0.016	100.44	0.98	-0.03	-1.513	-1.28
SFR 3T	0.062	4.05	1.01	-0.53	-0.049	-3.24
SW-TA3	0.007	45.29	1.07	0.73	-2.108	-2.86
Tijeras East	0.009	54.28	0.96	0.15	-1.564	-1.95
SFR 4T	0.0665	27.56	1.2	-0.47	-0.956	-2.51
PL-3	0.0074	43.68	1	-0.26	-1.783	-1.88
TRN-1	0.0213	209.08	0.95	-0.07	-1.769	-0.813
MRN-2	0.007	42.18	1.01	-0.19	-1.885	-2.02
TJA-2	0.008	28.95	1.12	-0.15	-1.737	-2.19

[a] mg/L = milligrams per liter.
[b] atm = atmosphere.

Table 2-5. Most Representative Data Used in This Investigation

	Alkalinity (mg/L[a] of $CaCO_3$)	Br (mg/L)	Cl (mg/L)	F (mg/L)	pH	SO4 (mg/L)	Ca (mg/L)	Fe (mg/L)	Mg (mg/L)	K (mg/L)	Na (mg/L)	NPN (mg/L)	Turbidity NTU[b]	Si (mg/L)	δD[c] (‰)	$\delta^{18}O$[c] (‰)
Burn Site Well	220	0.81	56	0.9	6.8	180	110	0.09	39	3.5	27	5	0.48	4.9	-73	-10.4
Coyote Springs	893	2.1	510	1.7	6.15	110	290	1.8	60	28	360	0.37	18.8	8.2	-87	-11.6
CWL-BW2	373	0.64	130	1.7	6.85	77	130	5.5	30	6.5	87	1.5	37.8	15	-74	-10.2
EOD Hill Well	1997	1.8	390	1.7	6.07	140	540	17	100	38	410	<0.05	5.23	24	-100	-13.8
Golf Course South	123	0.6	48	0.4	7.32	65	86	<0.02	17	2.4	21	19	0.25	12	-74	-10.3
Greystone	340	0.58	92	0.6	6.94	45	110	22	27	6	69	4.5	191	11	-73	-10.3
Hubbell Spring	238	0.35	34	0.9	6.2	180	82	<0.02	32	1.6	57	0.74		14	-76	-10.1
KAFB-10	65	0.3	130	1.3	7.58	48	27	1.6	11	6	70	0.8	30.2	5		
LF/DM-01	98	<0.05	6	0.5	7.93	27	30	0.03	4.7	2.1	18	<0.05	0.5	16	-100	-13.7
LF/DM-02	175	0.19	17	0.3	7.35	77	72	0.07	13	2.3	24	4.2	3.05	13	-74	-10.6
MVMW-J	168	0.1	8.5	0.4	7.76	25	51	2.9	6	3.9	23	11	59	32	-97	-13.5
MVMW-K	169	0.16	12	0.4	8.08	29	53	1.7	5.9	2.5	23	1.4		36	-99	-13.5
MWL-BW1	234	<0.1	25.6	0.79	7.53	42.5	55.8	0.057	20	3.5	56.9	5.6	1.9	14		
NW-TA3	153	0.21	17	0.4	7.51	75	61	0.09	15	4.4	22	6.2		15	-71	-10.3
Schoolhouse	402	0.71	150	1.4	6.82	60	140	2.2	25	6.1	92	3.9		10	-73	-10.1
Sol se Mete	225	0.4	27	0.5	7.34	65	100	<0.02	17	1.6	11	1.2		8.6	-78	-10.7
SFR 1	446	0.69	130	1.6	6.73	68	150	0.07	37	7.1	78	0.93	1	16	-73	-10.3
SFR 2	334	<0.1	140	1.9	6.83	75	120	0.1	33	6.5	73	0.86	0.79	14		
SFR 3P	329	0.7	140	1.7	6.85	94	120	0.93	28	4.6	87	0.96	7	14	-72	-10.3
SFR 3T	16	0.55	47	1.6	7.45	2200	450	0.02	41	5.3	500	<0.05	0.56	5.1	-92	-12.4
SW-TA3	190	0.2	23	1.3	8.2	42	45	0.96	11	4.8	55	3.8	20.8	15	-66	-9.8
Tijeras East	208	0.14	14	0.4	7.34	93	82	<0.02	11	1.6	27	2.6	1.2	11	-78	-10.9
SFR 4T	110	1	180	3	7.57	1900	57	0.05	3.4	2.5	1200	0.62	1.65	4.8		
PL-3	160	0.2	20	0.3	7.16	70	59	0.1	12	4.7	27	5	0.89	16		
TRN-1	610	0.7	130	0.9	6.65	71	100	0.05	52	9.2	160	0.3	2.31	14		
MRN-2	160	0.2	10	0.6	7.3	65	49	0.03	16	3.7	24	4.5	2.1	14		
TJA-2	110	1	72	0.2	7.3	61	80	<0.02	13	1.8	23	6	0.34	11		

[a] mg/L = milligrams per liter.

[b] NTU = nephelometric turbidity unit.

[c] δD and $\delta^{18}O$ values are from the September 1994 sampling.

3.0 Overview of Modeling Methods

Two types of geochemical modeling were used in this study: (1) mass-balance and (2) reaction-path. In the mass-balance approach, two groundwater analyses from the same (assumed) flow path are compared. If differences exist in the chemistries of chemical components, they are explained by mass transfer between the groundwater and the solid phases in the aquifer. Evaporation and mixing with other groundwater can also be modeled. For example, if chloride concentration increases from the upgradient to the downgradient sample, it could be that a chloride-bearing mineral (for example halite) dissolved, that an ion exchanged with chloride on a clay mineral surface, that water was lost through evapotranspiration, or that mixing occurred with a high-chloride groundwater. The selection of the correct process involves assimilating all available information about the rock types, groundwater hydrology, climate, and other groundwater chemical components. Rarely, if ever, will a unique set of chemical processes be defined.

With the mass-balance approach, multiple models can be defined that exactly match the observed results. With thermodynamic considerations, some of these models may be eliminated. For example, if a model requires gypsum to be precipitated, but gypsum is undersaturated in both the upgradient and downgradient groundwater samples, this model could be eliminated. The accuracy of the thermodynamic data must be considered when applying these criteria. In the gypsum example, if the solutions are only slightly undersaturated and the amount of gypsum precipitated is small, the model may be viable. Some subjectivity is usually involved on the part of the geochemist in making these determinations.

The mass-balance approach is an inverse problem in that the final composition is used in conjunction with the initial water composition to formulate the models. In contrast, the reaction-path approach is a forward problem, in which only the initial groundwater composition is used as input (Plummer et al. 1983). In the reaction-path approach, the initial groundwater composition is interacted with plausible phases (phases that the modeler has determined are reasonable to occur in the aquifer under consideration) in a stepwise method. At each step, saturation indices for plausible phases are examined. If a phase that was previously undersaturated becomes saturated, then it is necessary at this reaction step to begin to precipitate this phase. Thus, the results of a reaction-path simulation satisfy all thermodynamic constraints (mass-balance modeling does not consider thermodynamics). Therefore, reaction-path methods are preferred if a reasonable reaction path can be found.

The driving force for a reaction-path model is the stepwise addition of an irreversible reaction. The irreversible reaction could be the dissolution (or precipitation) of a mineral phase, the exsolution (or dissolution) of a gas, ion exchange, or a progressive mixing with another water; combinations of these processes could also be used. Time is rarely used as a reaction-progress variable because the required rate constants are typically unknown.

3.1 History of Modeling Methods

A paper by Garrels and Mackenzie (1967) is often cited as the founding work on the mass-balance (called material-balance by them) approach. In Garrels and Mackenzie (1967), the major-ion chemistry of spring water in the Sierra Nevada is modeled by considering interactions between shallow groundwater and the granite through which it passes. The initial composition is assumed to be the composition of an ephemeral spring in the area; the final composition is that of a perennial spring. The approach involved progressively subtracting phases from the final composition. The first step was to remove Cl by assuming that the Cl was added to the groundwater by the dissolution of halite (NaCl). Thus, when Cl was removed, an equimolar amount of Na was subtracted from the Na inventory. Plausible phases, including halite, gypsum, kaolinite, Ca-montmorillonite, CO_2 gas, calcite, silica, biotite, and plagioclase, were progressively removed to account for the major-ion composition of the final spring water.

The pioneering work of Helgeson (1968) provided a mathematical approach to solve reaction-path simulations. With this approach, both irreversible and reversible (partial equilibrium) reactions are integrated into a series of linear differential equations. These methods have been applied to define reaction paths responsible for mineralogic sequences observed in hydrothermal ore deposits (Helgeson 1979).

The U.S. Geological Survey (USGS) developed the widely used computer codes BALANCE (Parkhurst et al. 1982) and NETPATH (Plummer et al. 1991) to solve mass balance problems and PHREEQE (Parkhurst et al. 1980) to solve reaction-path problems. Plummer et al. (1983) describe the mathematical development of the USGS codes and provide examples of their use. The example used by Plummer et al. (1983) is a study of an aquifer in Florida. The chemistry of groundwater was determined in three wells assumed to lie along a flow path. Twelve mass-balance models were found to satisfy the constraints of seven plausible phases. Carbon and sulfur isotopes were used to further constrain the system and the reaction path. Simulations involved both closed (to CO_2) and open systems. The purpose of the modeling was to determine what chemical reactions are occurring in the aquifer. Plummer et al. concluded that the processes responsible for the groundwater evolution are irreversible incongruent dolomite dissolution, gypsum dissolution, and sulfate reduction; the system was open to CO_2 initially and reaction with organic carbon occurred.

Anderholm (1988) studied the groundwater geochemistry of the Albuquerque-Belen Basin as part of a water resources investigation. Anderholm's study was cited in the GJPO Statement of Work as a model that could be used as a guide in this investigation. Anderholm (1988) presented the geochemical data as spatial plots and Piper diagrams and included modeling that used the Garrels and MacKenzie (1967) material-balance approach to aid in the interpretations of groundwater origins.

For his northern area, which includes the Sandia/KAFB site, Anderholm (1988) concluded that several wells northeast of Albuquerque with relatively low specific conductance are representative of groundwater flowing into the basin from the eastern

Sandia Mountains. He also indicates that several wells to the northeast of Albuquerque have high Cl concentrations (to 96 milligrams per liter [mg/L]). These wells are near the basin boundary faults. Anderholm suggests that these elevated Cl concentrations are related to evolving geothermal water upwelling along the faults.

Note that in all these studies flow paths were ***assumed*** and the modeling was used as a tool to help characterize the chemical reactions that are likely to be occurring in the aquifer. Thus, the modeling is used as a characterization tool rather than a diagnostic tool capable on its own of defining flow paths. Even in Anderholm's study, where the goals included interpreting groundwater origins, the flow paths were based on geologic, geohydrologic, and spatial chemistry—not strictly on model results.

3.2 Mathematical Treatment

The mass balance approach is described by the following equation (Plummer et al. 1983):

$$\left\{ \sum_{p=1}^{P} \alpha_p \, b_{p,k} = \Delta m_{T,k} \right\} \quad k = 1,J \tag{1}$$

where

α_p = net mass transfer in moles of the p^th^ plausible phase among the *P* total reactant and product phases in the reaction,

$b_{P,k}$ = stoichiometric coefficient of the k^th^ component in the p^th^ phase,

Δ = difference (final value minus initial value),

$m_{T,k}$ = total molality of the k^th^ component in solution, and

J = number of components.

The computer program PHREEQE (Parkhurst et al. 1980) was used to perform the reaction-path calculations. This program solves a set of nonlinear equations that define

(1) electrical neutrality;

$$\sum_{i=1}^{I} Z_i \cdot m_i = 0 \tag{2}$$

(2) mass balance;

$$\sum_{i=1}^{I} c_{i,j} \cdot m_i = TOT_j + \sum_{p=1}^{P} b_{p,j} \cdot MIN_p \textit{ for each } j \tag{3}$$

(3) mineral equilibrium;

$$\sum_{j=1}^{J} b_{p,j} \cdot \log\,(a_j) = \log\,(K_p) \textit{ for each } p \tag{4}$$

and (4) mass action for aqueous species

$$\log\,(a_i) = \log\,(K_i) + \sum_{j=1}^{J} c_{i,j} \cdot \log\,(a_i)$$

where

I = number of aqueous species,
Z_i = charge on the ith species,
m_i = molarity of the ith aqueous species,
$c_{,i,j}$ = stoichiometric coefficient of the jth master species in the ith aqueous species,
TOT_j = total concentration of the element corresponding to the jth master species preceding any mineral dissolution or precipitation,
P = number of mineral phases,
$b_{,pj}$ = stoichiometric coefficient of the jth master species in the pth mineral,
MIN_p = moles of the pth mineral transferred into (+) or out of (-) the aqueous phase,
J = number of master species,
a_j = activity of the jth master species,
a_i = activity of the ith ion pair, and
K_i = equilibrium constant for the mass action equation for the ith species.

PHREEQE has a flexible input that allows the user to drive the chemical equilibrium with an (or a set of) irreversible reaction steps.

3.3 Model Assumptions and Uncertainties

Multiple mass-balance models can be defined to satisfy all known geochemical constraints for a groundwater system. Elimination of those models that are less likely to reflect reality involves assimilating all other site information (e.g., groundwater hydrology, geology, climate) that bears on the analysis. Sufficient information is rarely available on the composition of the subsurface; thus, the list of plausible phases (and their exact chemical compositions) is usually a major source of uncertainty.

More than one irreversible process probably occurs simultaneously to drive the chemical evolution of most groundwater systems. The relative rates of the driving reactions are required to accurately model these systems; however, these rates are seldom known.

In the literature examples of mass-balance and reaction-path models such as those summarized in Section 3.1, the two or more groundwaters being modeled are assumed to be located along a flow path. The purpose of the modeling was to determine what chemical reactions caused the observed changes in groundwater composition. The modeling exercise was aimed at limiting the number of chemical reactive models that satisfied the constraining data. The reactive processes used in these models were then believed to represent the most likely processes that occur in the aquifer.

In contrast to a goal of understanding chemical processes occurring in the aquifer, the primary goal of the current study at Sandia/KAFB was to define groundwater flow paths and recharge areas. To accomplish this goal, we wish to test the hypothesis that two groundwater samples are located on the same flow path. Compositions of the two groundwaters are compared and modeled. Models are evaluated and are accepted if they provide a reasonable explanation of the groundwater system. The test of "reasonableness" is necessarily subjective because no unique solutions are found. Thus, a geochemical evaluation is best used to help evaluate conceptual models derived from geologic and groundwater hydrologic investigations.

Because of the uncertainty that is inherent in sampling and analyzing groundwater, small differences in analytical values between two wells may not reflect geochemical processes. Thus, the interpretations made in the following sections emphasize the largest compositional variations.

3.4 Statistical Evaluation

A statistical evaluation was performed to determine if any of the differences in analytical values between two wells could be solely the result of random sampling and analysis uncertainties. If so, the analyte may have been "conserved" along the flow path without having undergone any chemical reaction. The statistical evaluation is used to determine which elements display the largest variation.

The statistical analysis, however, cannot prove that an element is conserved. Take, for example, Ca which is controlled by calcite dissolution. Dilution of a calcite-equilibrated groundwater followed by the addition of Ca due to re-equilibration would produce the original Ca concentrations and, yet, Ca would not have been conserved.

3.4.1 Methods

T-statistics were computed for the three pairs of wells used in the interpretive section (Section 5). The data are from up to eight sampling rounds (Appendix A). SFR-4T has only one sampling period, so a statistical evaluation could not be performed. Suspect data were not used in the evaluation. The variances due to sampling and analysis imprecision should be normally distributed, which meets the requirement of the T-test method.

As an example of the T-test method, pairs of chloride data used in the comparison of EOD Hill well and Coyote Springs (Appendix A) are 422.7/523.2, 434.1/528.2, 410/420, 420/410, 400/510, 420/530, 390/540, 390/510, and 369/500. The computed T-statistic is 5.0, whereas the tabulated value for $\alpha=0.05$ is 2.3, indicating that the variation is outside the range attributed to random fluctuations. It is concluded that Cl concentrations are significantly different between these two wells.

3.4.2 Results

The results of the statistical evaluation are presented in Table 3-1. With the exception of SO_4 and pH in the EOD Hill/Coyote Springs pair and SO_4 in the SFR-3P/EOD Hill pair, all analytes showed variation in excess of that expected due to random sampling and analysis imprecision.

Table 3-1. Results of T-Tests

	EOD Hill	Coyote Springs	Result	CWL-BW2	MWL-BW1	Result[c]	SFR-3P	EOD Hill	Result[c]
	t	*t		t	*t		t	*t	
Ca	17.9	2.4	+	15.0	2.4	+	66.4	3.2	+
Na	5.4	2.4	+	15.9	2.4	+	125.1	3.2	+
K	8.4	2.3	+	49.5	2.4	+	157.4	3.2	+
Mg	20.8	2.4	+	18.8	2.4	+	31.0	3.2	+
Alk	14.3	2.6	+	8.0	2.6	+	34.3	3.2	+
SO_4	1.3	2.4	0	6.6	2.4	+	3.2	3.2	0
Cl	5.0	2.3	+	35.8	2.6	+	20.6	3.2	+
pH	2.0	2.3	0	7.6	2.4	+	25.6	3.2	+

t Calculated t statistic.

*t Rejection t value for α of .05.

[c] + result means the two populations are significantly different at the $\alpha = .05$ level.

0 Result means no significant difference in the 2 populations.

4.0 Description of the Sandia/KAFB Site

This section summarizes the geology, surface-water hydrology, groundwater hydrology, groundwater geochemistry, and mineralogy as they pertain to the current project. More detailed descriptions are in Sandia/NM (1994b) and the references in that report. Figure 4–1 presents stratigraphy of the site, and Figure 4–2 presents the geology of the Sandia/KAFB site and wells.

4.1 Geology

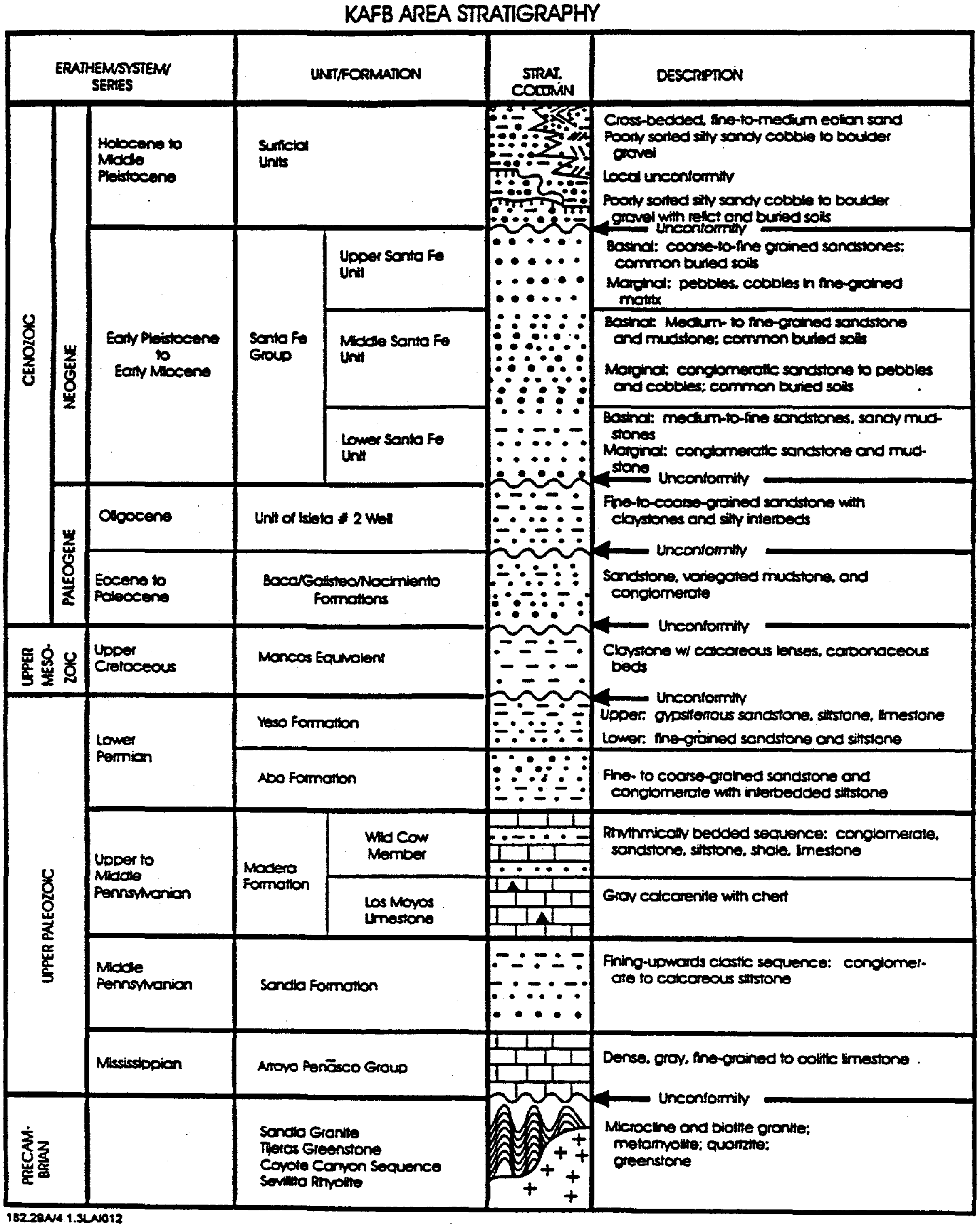
The Sandia/KAFB site lies in the boundary area between crystalline bedrock mountains (Manzanita Mountains) to the east and Tertiary/Quaternary basin fill to the west. Major northeast-southwest trending faults are characteristic of rifting (crustal extension) processes that formed the basin. The Manzanita Mountains are composed of Precambrian schist, gneiss, and granite that is capped by Paleozoic sediments. In the transition zone faults, exposed blocks of basement (such as the block of Madera Limestone exposed at EOD hill) exposed indicate a complex structural history.

The basin fill is a thick (more than 14,500 feet) sequence of alluvial fans deposited from the eastern highlands and fluvial sediments from the Rio Grande River. These deposits predominately consist of the Tertiary Santa Fe Group with a thin Quaternary alluvial cover. The sedimentary grains consist of quartz, clay, pumice fragments, and a wide variety of lithic fragments including granite, schist, greenstone, limestone, and clastics.

4.2 Surface-Water Hydrology

Groundwater is likely to be influenced by the Rio Grande River, a major perennial north-to-south flowing stream located about 5 miles west of the site boundary. Much of the Rio Grande water is diverted into irrigation ditches. The Rio Grande loses water to the aquifer in the vicinity of Sandia/KAFB (Yapp 1985). Two major arroyos (Tijeras and Coyote) drain the mountainous area in the eastern portion of the site to the Rio Grande River. Because the valley receives only about 9 inches of precipitation per year and evapotranspiration is high, little vertical infiltration is expected into the Santa Fe Group. The Sandia/NM Site-Wide Project is collecting infiltration data to help determine if all or almost all the vertical recharge into the basin fill is from arroyos during flood stages.

As much as 30 inches of precipitation falls in the mountains east of the Sandia/KAFB site. The higher precipitation and lower evapotranspiration are likely to produce greater infiltration and groundwater recharge in the mountains than in the valley.



KAFB AREA STRATIGRAPHY

ERATHEM/SYSTEM/ SERIES			UNIT/FORMATION		STRAT. COLUMN	DESCRIPTION
CENOZOIC	NEOGENE	Holocene to Middle Pleistocene	Surficial Units			Cross-bedded, fine-to-medium eolian sand Poorly sorted silty sandy cobble to boulder gravel Local unconformity Poorly sorted silty sandy cobble to boulder gravel with relict and buried soils Unconformity
		Early Pleistocene to Early Miocene	Santa Fe Group	Upper Santa Fe Unit		Basinal: coarse-to-fine grained sandstones; common buried soils Marginal: pebbles, cobbles in fine-grained matrix
				Middle Santa Fe Unit		Basinal: Medium- to fine-grained sandstone and mudstone; common buried soils Marginal: conglomeratic sandstone to pebbles and cobbles; common buried soils
				Lower Santa Fe Unit		Basinal: medium-to-fine sandstones, sandy mudstones Marginal: conglomeratic sandstone and mudstone Unconformity
	PALEOGENE	Oligocene	Unit of Isleta # 2 Well			Fine-to-coarse-grained sandstone with claystones and silty interbeds Unconformity
		Eocene to Paleocene	Baca/Galisteo/Nacimiento Formations			Sandstone, variegated mudstone, and conglomerate Unconformity
UPPER MESOZOIC		Upper Cretaceous	Mancos Equivalent			Claystone w/ calcareous lenses, carbonaceous beds Unconformity
UPPER PALEOZOIC		Lower Permian	Yeso Formation			Upper: gypsiferous sandstone, siltstone, limestone Lower: fine-grained sandstone and siltstone
			Abo Formation			Fine- to coarse-grained sandstone and conglomerate with interbedded siltstone
		Upper to Middle Pennsylvanian	Madera Formation	Wild Cow Member		Rhythmically bedded sequence: conglomerate, sandstone, siltstone, shale, limestone
				Los Moyos Limestone		Gray calcarenite with chert
		Middle Pennsylvanian	Sandia Formation			Fining-upwards clastic sequence: conglomerate to calcareous siltstone
		Mississippian	Arroyo Peñasco Group			Dense, gray, fine-grained to oolitic limestone Unconformity
PRECAMBRIAN			Sandia Granite Tijeras Greenstone Coyote Canyon Sequence Sevillita Rhyolite			Microcline and biotite granite; metarhyolite; quartzite; greenstone

182.29A/4 1.3LA/012

Figure 4–1. Stratigraphic Column for the Sandia/KAFB Area (Sandia 1993)

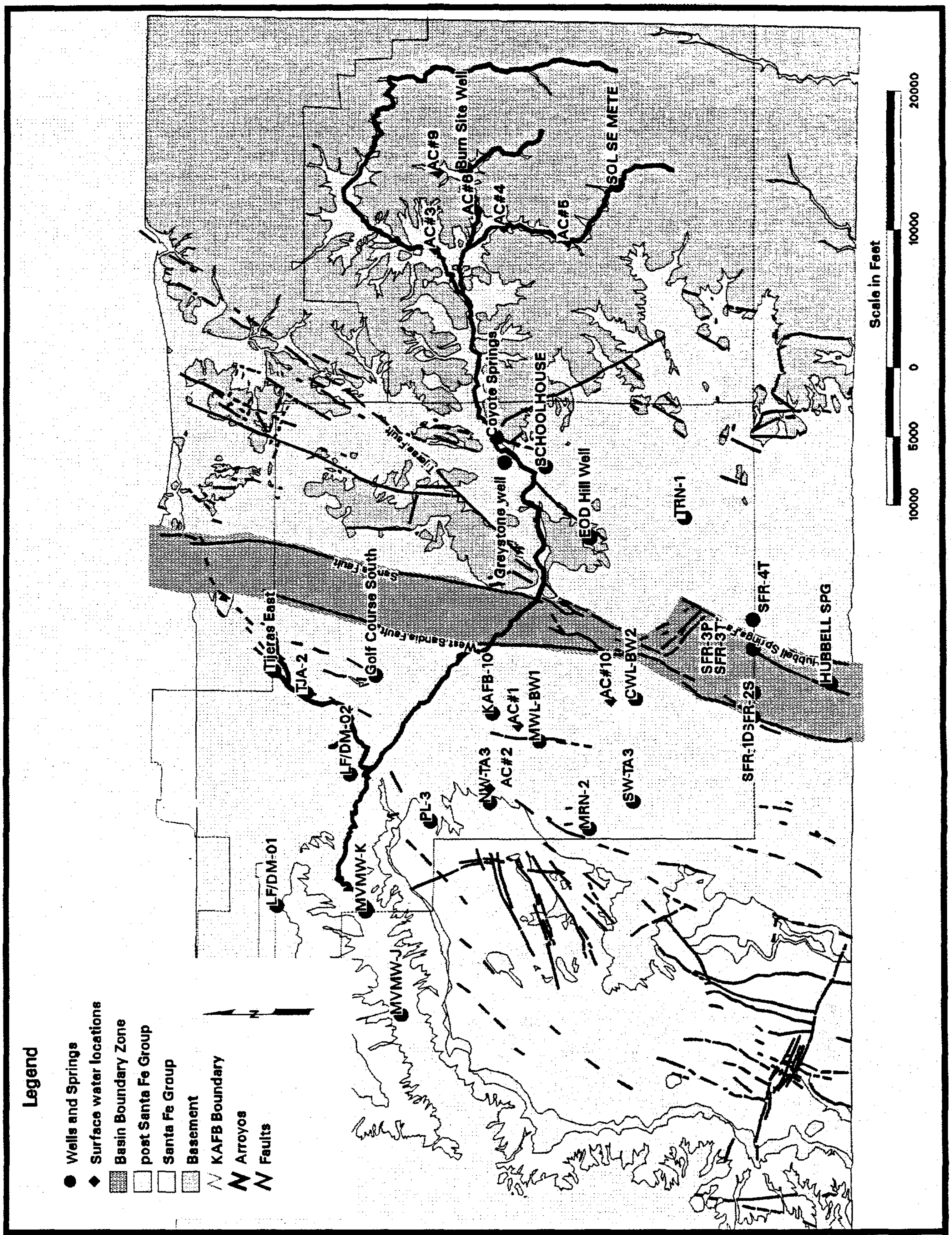


Figure 4-2 : Location Map for the SNL/KAFB Site

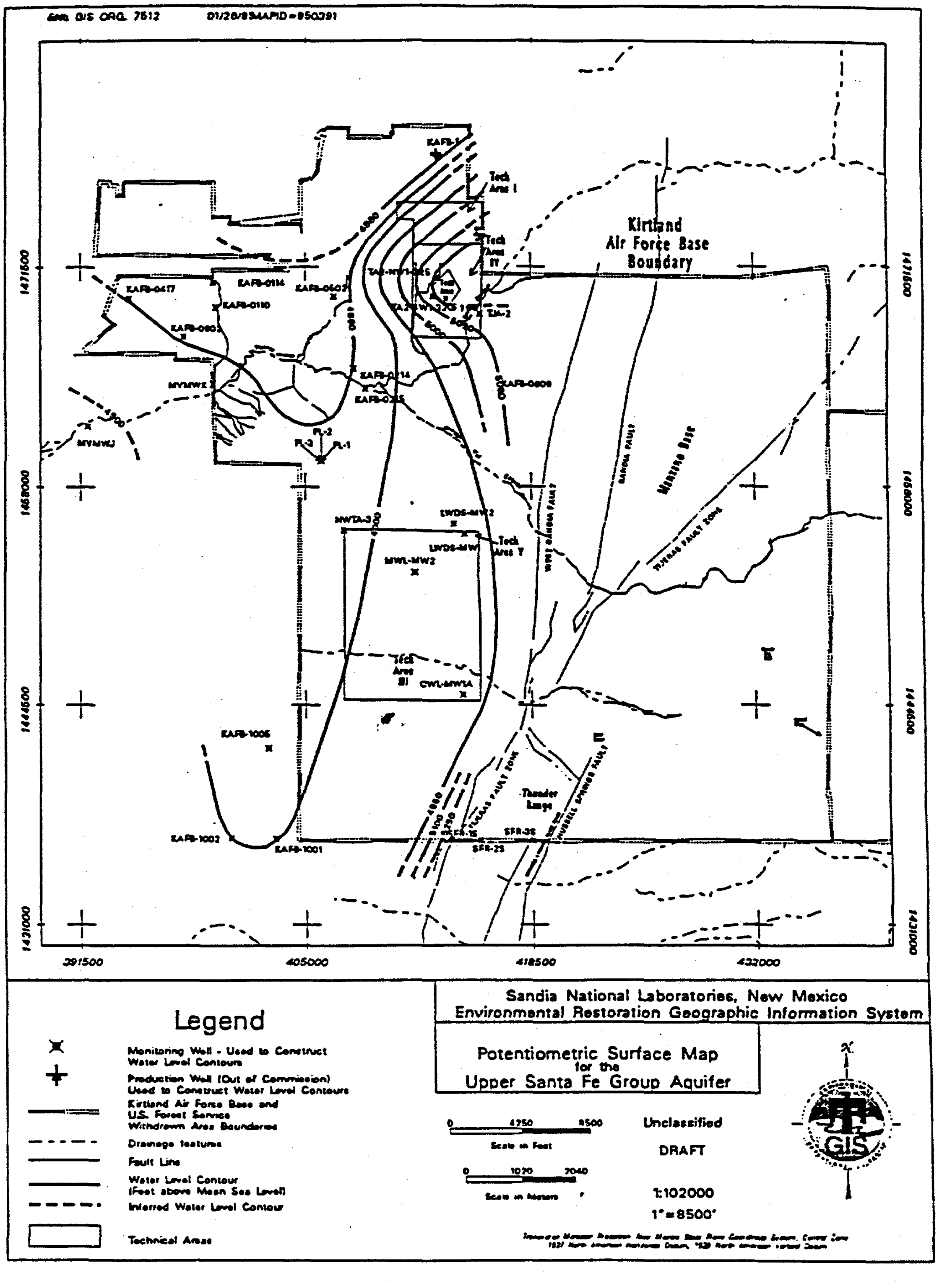


Figure 4-3. Potential Surface Map, July 1993 (Sandia/NM 1993)

4.3 Groundwater Hydrology

Figure 4–3 shows a potentiometric map of the groundwater for the Sandia/KAFB site. Data for this map are from wells with screens in a variety of geologic units. Although the map is probably an accurate portrayal of the regional water table, local perturbances are likely. Regionally, groundwater flows from the highlands toward the valley floor; east to west across the site. Groundwater also flows easterly from the Rio Grande River. Pumping from the Santa Fe Group aquifer for the city of Albuquerque causes the cone of depression seen in the 4900-foot contour on Figure 4–3. This pumping adds a northwest component to the groundwater flow direction at the site.

4.4 Groundwater Major-Ion Geochemistry

Figure 4–4 is a Piper diagram of the MRD for the Sandia/KAFB site. Piper diagrams plot concentration ratios, expressed in milliequivalent (meq) per liter of major dissolved ions, and are useful for classifying groundwaters. Each groundwater analysis is plotted on a cation triangle, an anion triangle, and a diamond-shaped cation-plus-anion plot. The cation (Ca, Mg, and Na plus K) triangle is divided into four equivalent triangles. Points falling into the apical triangles are said to be dominated by that cation, whereas those in the center do not portray a particular dominance. The anion triangle is also divided into four equivalent triangles. Clusters of data may indicate similar origins. Data presented in Figure 4–4 indicate that most of the groundwater at the Sandia/KAFB site is calcium-bicarbonate type. Groundwater from KAFB–10 is sodium-chloride type and from SFR–3T is calcium/sodium-sulfate type.

The spatial distribution of Cl is shown as a spot plot in Figure 4–5. The size of the spot indicates the concentration of Cl at that location. Each spot is labeled with the concentration in milligrams per liter. All wells west of the Hubbell Springs Fault are screened in the Santa Fe Group, while those east of the fault are screened in a variety of formations (Table 2–1). Figure 4–6 shows the distribution of Cl concentrations for only those wells that are screened in the Santa Fe Group. The distribution of Cl indicates relatively high concentrations in the Santa Fe Group near the faults, with progressively lower concentrations in the basin to the west. Because two of the wells (KAFB–10 and CWL–BW2) with particularly high Cl concentrations were screened at greater depths (Table 2–1) than other wells, Cl concentrations may be contributed from the deep basin. High Cl concentrations in KAFB–10 may be due to sampling problems; the well was sampled without purging (verbal communication with F. Lauffer).

Samples from the EOD Hill well and Coyote Springs display elevated Cl concentrations (Figure 4–5). These two sampling locations also have elevated concentrations of Ca, Na, C, Mg, K, Br, and ionic strength (Appendix C and Table 2–5). As indicated on the Stiff diagrams in Figure 4–7, the groundwater composition of the EOD Hill well is similar to Coyote Springs except for concentrations of Ca and HCO_3. Stiff diagrams provide a graphical display of multiple-ion concentrations that are absolute values, unlike Piper diagrams which are ratios.

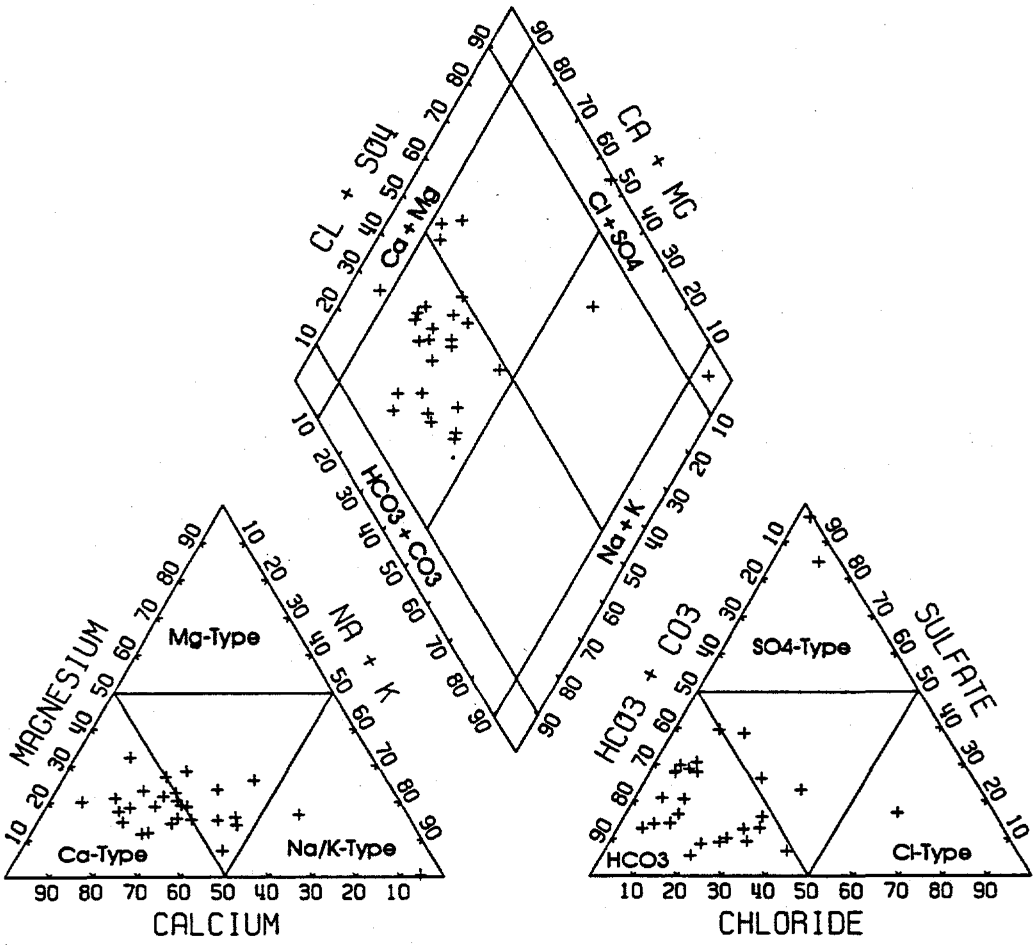


Figure 4–4. Piper Diagram of the MRD from All Wells and Springs Used in This Study

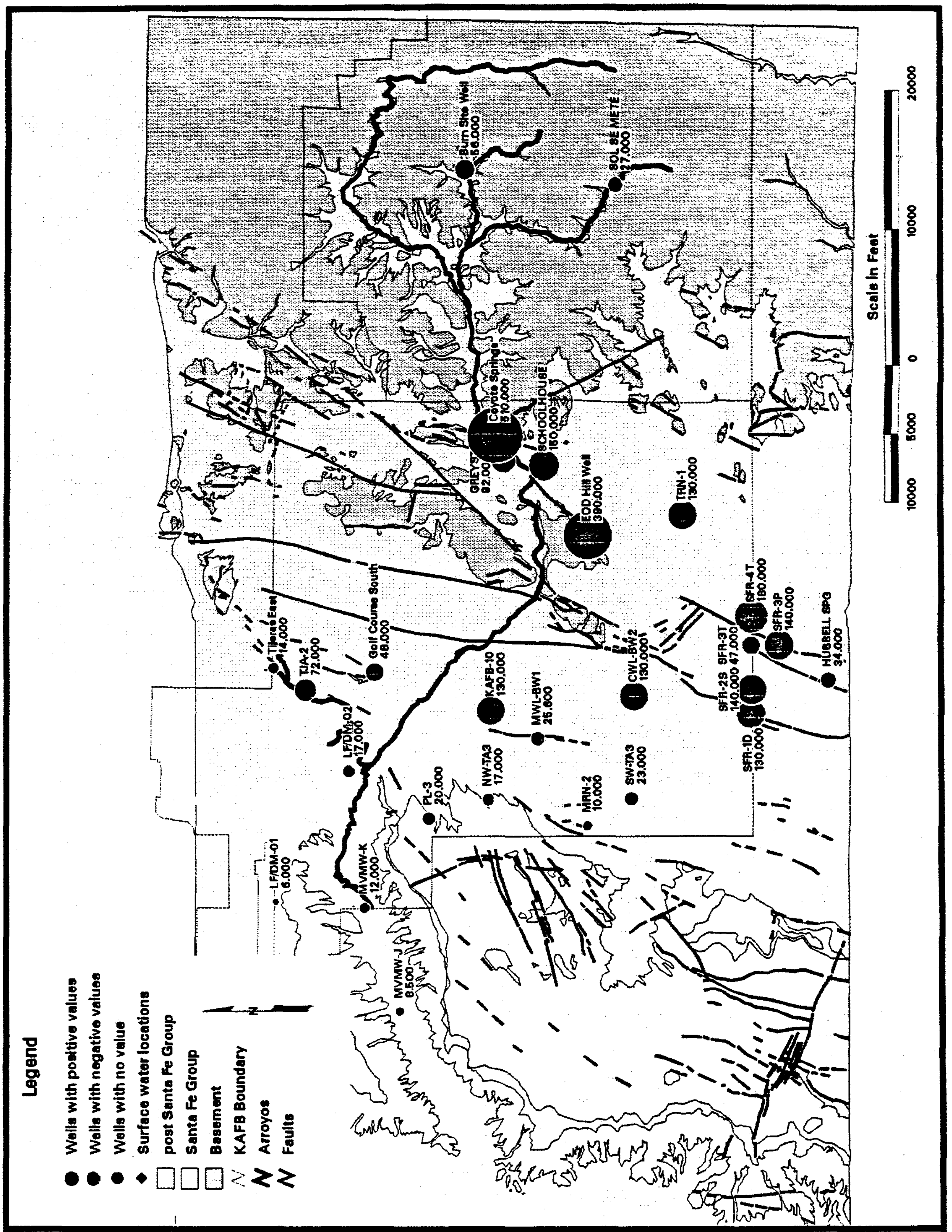


Figure 4-5 : Spot Plot for Cl (mg/L): all MRD wells

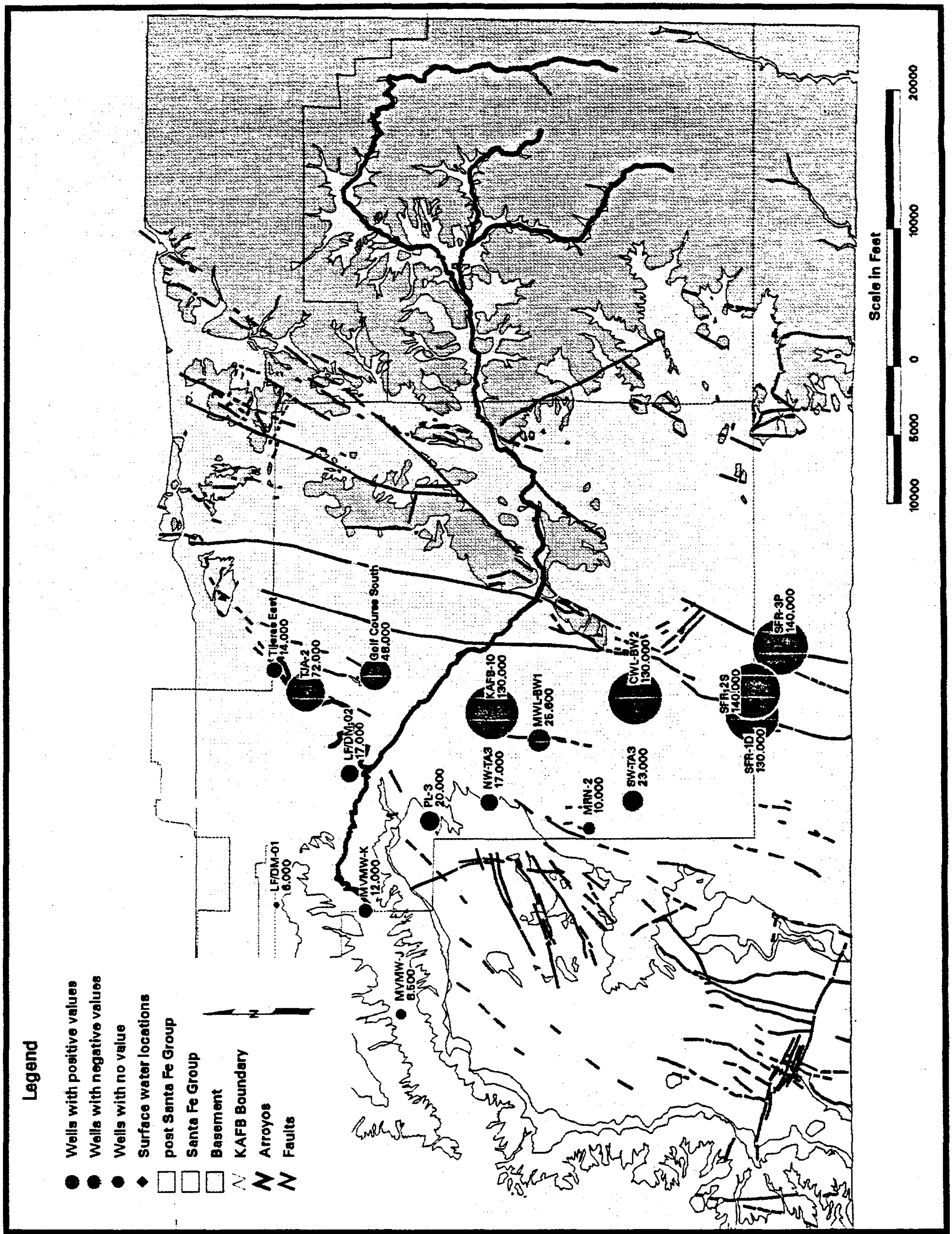


Figure 4-6 : Spot Plot for Cl (mg/L): only those MRD wells screened in the Santa Fe Group

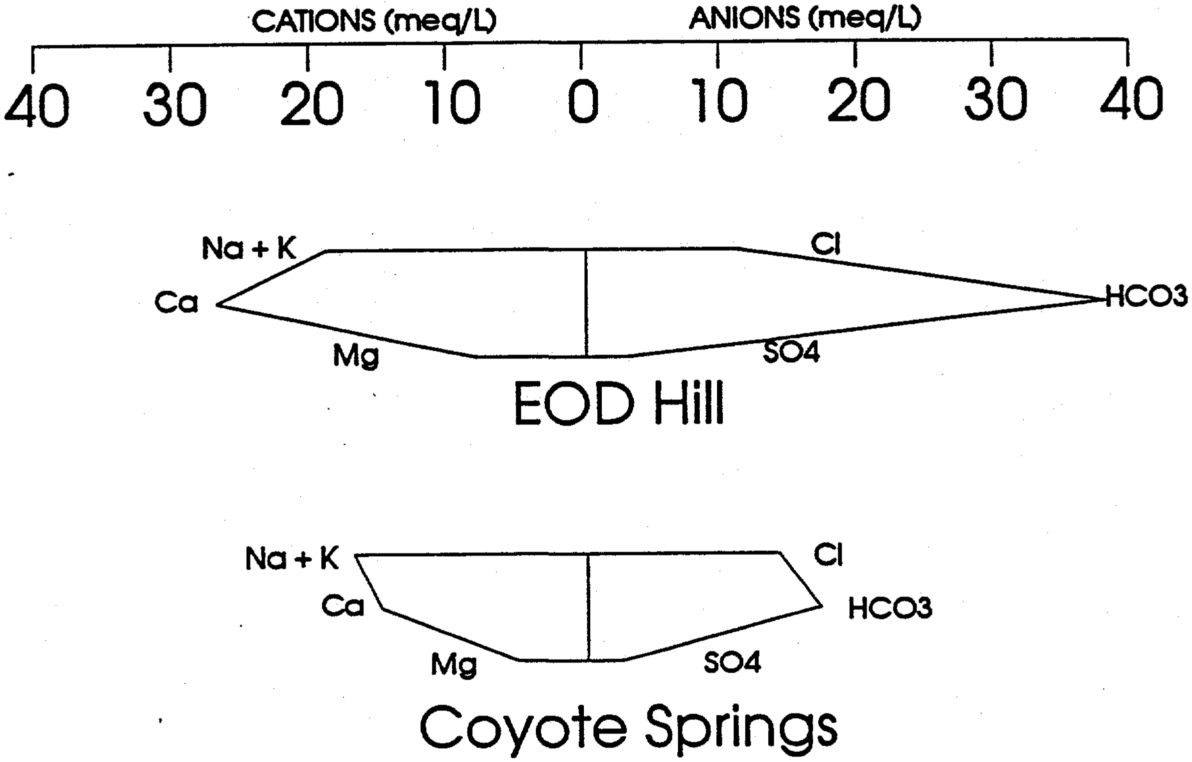


Figure 4–7. Stiff Diagrams for EOD Hill and Coyote Spring (MRD)

Sulfate concentrations in the Santa Fe Group show no obvious trends over the basin. However, SFR-3P, which is closest to the Hubbell Springs fault, has the highest SO_4 concentration, whereas MVMW-J, which is farthest from the fault, has the lowest value (Figure 4-8). Five wells (SFR-1, SFR-2, SFR-3P, SFR-3T, and SFR-4T) were sampled in an east-west line along South Fence Road (Figure 4-2). Wells SFR-3P and SFR-3T are 40 feet apart and completed at different levels. SFR-3P is screened from 175 to 195 feet in the Santa Fe Group. SFR-3T crossed the fault and is screened from 713 to 733 feet in the Lower Tertiary unit in the footwall. Well SFR-4T is drilled into the footwall and is screened in Lower Tertiary. Wells SFR-1 and SFR-2 are screened in Santa Fe Group.The groundwater chemistries of the Santa Fe Group wells (SFR-1, SFR-2, and SFR-3P) along South Fence Road are similar (Figure 4-9). The groundwater chemistry of the wells that sample the footwall (SFR-3T and SFR-4T) is substantially different from the hanging wall wells (SFR-1, SFR-2, and SFR-3P), as shown in Figure 4-9. Wells SFR-3T and SFR-4T have high concentrations of SO_4, but differ markedly in the cation composition. SFR-3T is high in Ca, whereas, SFR-4T is high in Na plus K.

Nitrate plus nitrite (NPN) concentration is anomalously high at the Golf Course South well (Figure 4-10). This well is located on the golf course where artificial watering has greatly increased the amount of effective precipitation. The MVMW-J well, which is located at a tree farm, is also high in NPN. The high NPN concentrations in Golf Course South and MVMW-J wells are probably due to the application of high-nitrate fertilizers. Groundwater from the Golf Course South well also has the highest cation/anion charge imbalance of any of the samples (Table 2-4 and Appendix C).

4.5 Stable Isotopes of Oxygen and Hydrogen

Isotopic data for δD and $\delta^{18}O$ concentrations in groundwater and surface water samples were collected by Site-Wide Project personnel during June and September 1994 (Tables 4-1 and 4-2).

All values are reported as δD (deuterium) or $\delta^{18}O$ where

$$\delta = \left(\frac{R_{Sample}}{R_{Standard}} - 1 \right) 1000 \qquad (6)$$

R_{Sample} is the D/H or $^{18}O/^{16}O$ in the sample and $R_{Standard}$ is the ratio in a standard of ocean water designated Standard Mean Ocean Water or SMOW. Thus, a groundwater sample with δD of -100‰ (parts per thousand) is 10 percent lighter than SMOW.

Groundwater δD ranged from -100 to -61‰; $\delta^{18}O$ ranged from -13.9 to -8.9‰. The lightest ratios were at EOD Hill and the heaviest at KAFB-10. The isotopic values in

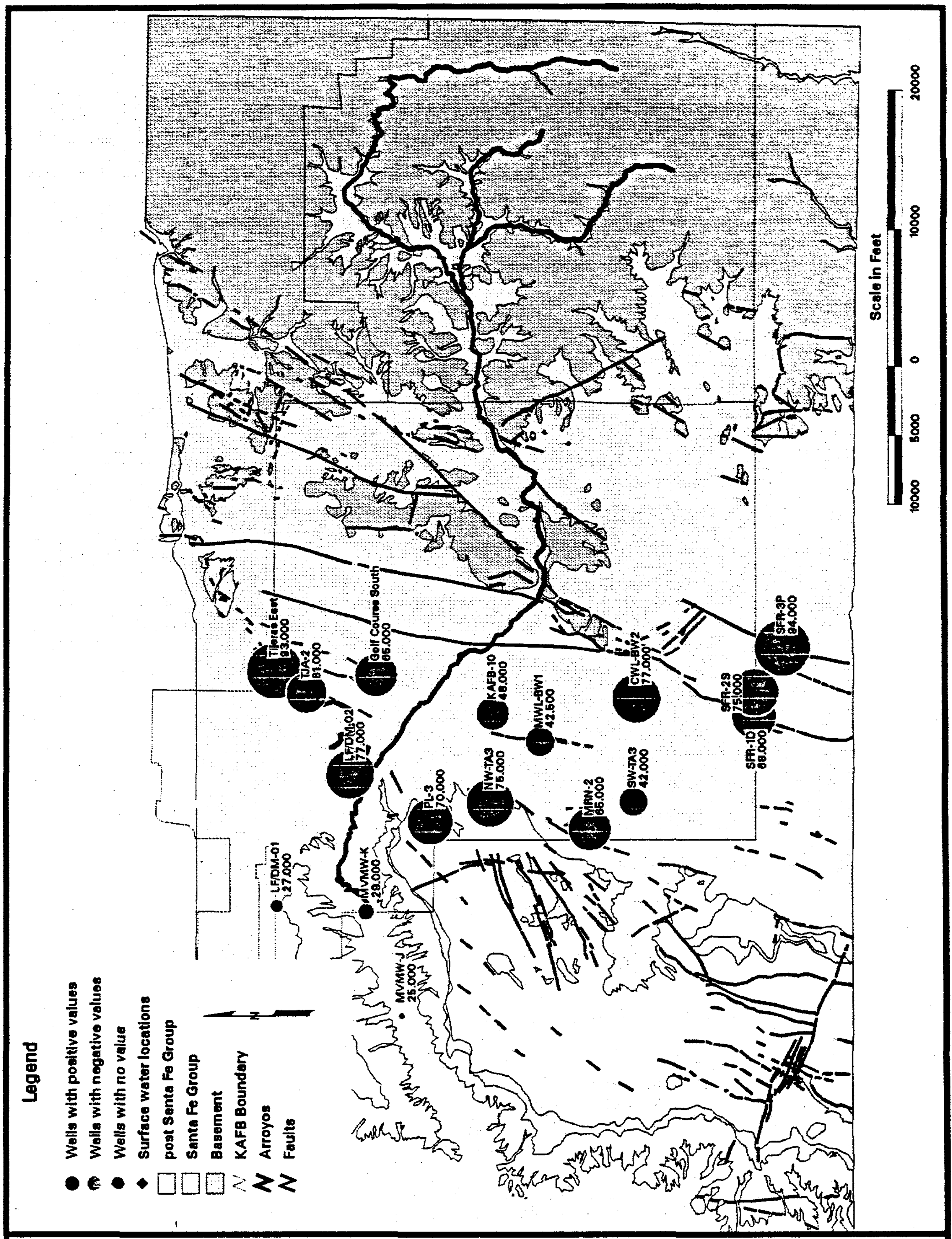


Figure 4-8 : Spot Plot for SO4 (mg/L): only those MRD wells screened in the Santa Fe Group

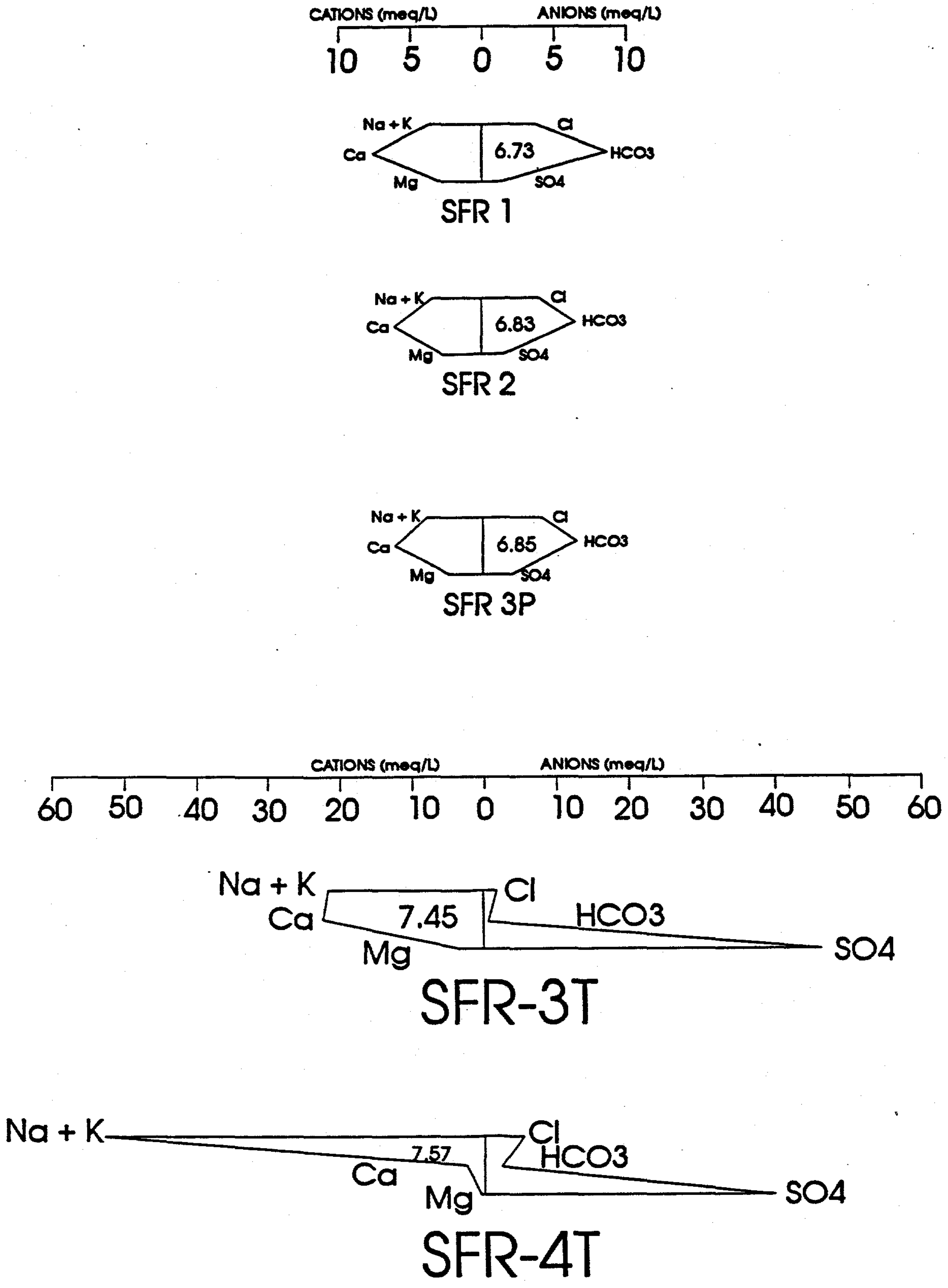


Figure 4-9. Stiff Diagrams for the South Fence Road Wells (MRD)

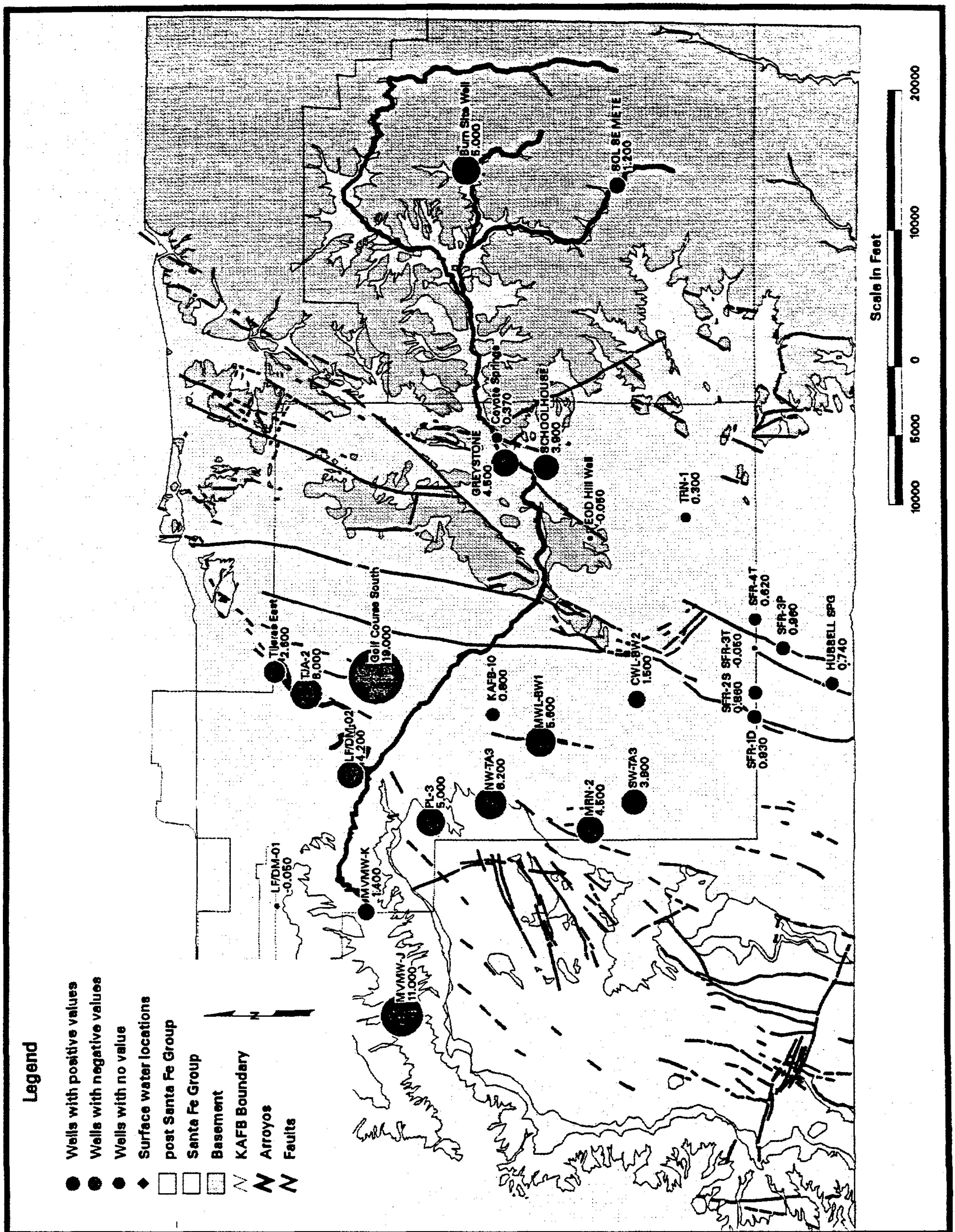


Figure 4-10 : Spot Plot for NPN (mg/L): all MRD wells

KAFB-10 may result from borehole evaporation due to inadequate sampling methods as suggested in Section 4.4. Values of $\delta^{18}O$ and δD were significantly higher in the surface water samples ranging from -11.3 to 1.5‰ and -80 to 10‰, respectively. The small variation in $\delta^{18}O$ and δD values between the two groundwater samplings (Table 4-1) provides confidence in the analytical precision of the values; the maximum difference in $\delta^{18}O$ is 0.3‰ and in δD values is 5‰. This small variation also suggests that the $\delta^{18}O$ and δD values remain constant over seasons although no spring or winter samplings were made.

Table 4-1. Oxygen and Hydrogen Isotopic Results for Groundwater Collected in 1994[a]

	$\delta^{18}O$ (‰)		δD (‰)	
Location	**June**	**September**	**June**	**September**
Burn Site	-10.5	-10.4	-78	-73
Coyote Springs	-11.5	-11.6	-84	-87
CWL-BW2	-10.2	-10.2	-72	-74
EOD Hill	-13.9	-13.8	-100	-100
Golf Course South	-10	-10.3	-74	-74
Greystone	-10.1	-10.3	-73	-73
Hubbell Spring	-9.9	-10.1	-71	-76
KAFB-10	-8.9		-61	
LF/DM-01	-13.6	-13.7	-100	-100
LF/DM-02	-10.6	-10.6	-74	-74
MVMW-J	-13.5	-13.5	-97	-97
MVMW-K	-13.2	-13.5	-96	-99
MWL-BW1	-9.2		-63	
NW-TA3	-10.4	-10.3	-72	-71
Schoolhouse	-10.2	-10.1	-71	-73
Sol se Mete Spring	-10.7	-10.7	-77	-78
SFR-1	-10.3	-10.3	-72	-73
SFR-3P	-10.3	-10.3	-74	-72
SFR-3T		-12.4		-92
SW-TA3	-9.8	-9.8	-67	-66
Tijeras East	-10.6	-10.9	-78	-78

[a] Data supplied by F. Lauffer (Sandia/NM).

Table 4-2. Oxygen and Hydrogen Isotopic Results for Surface Water Collected in 1994[a]

Location	$\delta^{18}O$ (‰)	δD (‰)	Date
AC-1	1.5	10	06/19/94
AC-1	-4.5	-26	08/01/94
AC-2	0.7	0	06/19/94
AC-3	-9.4	-58	07/21/94
AC-3	-10.3	-65	07/26/94
AC-4	-6.7	-42	08/01/94
AC-4	-9.5	-66	08/15/94
AC-5	-5.6	-42	07/17/94
AC-5	-6.1	-39	07/31/94
AC-6	-10.5	-71	08/15/94
AC-9	-11.3	-80	08/15/94
AC-10	-9.4	-64	08/14/94
Coyote Springs	-6	-42	08/01/94

[a] Data supplied by F. Lauffer (Sandia/NM).

In contrast, the surface water $\delta^{18}O$ and δD values varied significantly between two sampling periods in the same month (Table 4-2). For example, for two August samplings of AC-4 the $\delta^{18}O$ values varied by 2.8‰ and δD by 24‰. Values of δD for AC-1 varied from -26 to 10‰ from June to August.

The $\delta^{18}O$ and δD results are plotted on Figure 4-11 along with the meteoric water line. The meteoric water line is a best fit line to $\delta^{18}O$ and δD data from numerous samples of precipitation collected worldwide (Craig 1961). Comparisons to the meteoric water line are universally used to help interpret $\delta^{18}O$ and δD results. The meteoric water line has the equation

$$\delta D=8\delta^{18}O+10(\text{‰}) \tag{7}$$

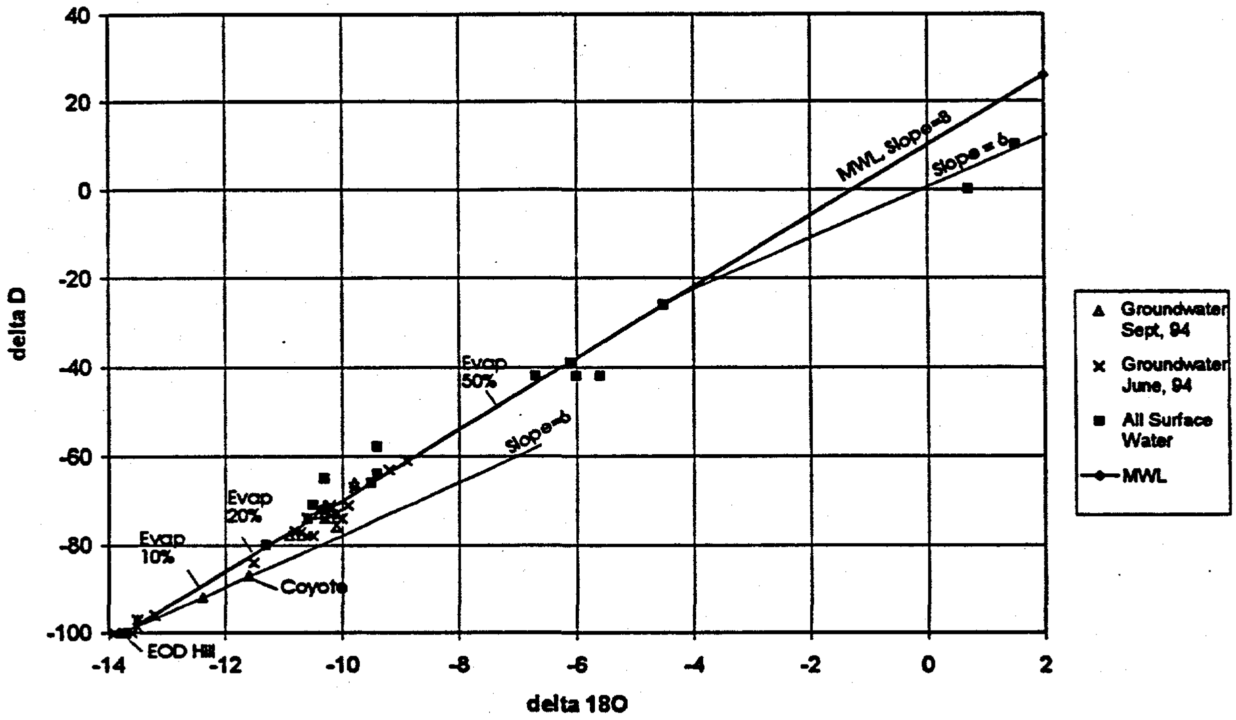


Figure 4–11. δD - $\delta^{18}O$ Plot of Water Samples from Sandia/KAFB

Nearly all groundwater samples from the Sandia/KAFB site plot on or near the meteoric water line. Some samples show modest departures to heavier $\delta^{18}O$ values. The surface-water samples show larger departures, particularly for the heaviest two samples.

A spot plot shows that anomalously light δD values occur at EOD Hill and at three wells (LF/DM-01, MVMW-K, and MVMW-J) in the western part of the region closest to the Rio Grande River (Figure 4-12). When only Santa Fe Group wells are examined, two groups of δD values are apparent: a western group with light values ranging from -97 to -100‰ and an eastern group with heavier values ranging from -66 to -79‰ (Figure 4-13).

4.6 Mineralogy

This study uses geochemical signatures to understand flow paths of groundwater. As groundwater flows through an aquifer, dissolved chemicals can be transferred to or from solid grains. To reliably predict flow-path chemistry, the availability of reactive solid phases must be known. Data for the mineralogy come from lithologic logs of the wells supplied by Sandia/NM, thin section descriptions of core samples supplied by GRAM, Inc. (subcontractor for the Site-Wide Project), and field observations.

The mineralogy of the detrital grains is reasonably well established from these sources of information. The presence or absence of minor authigenic phases (such as iron oxides) that coat grain surfaces or fill hairline fractures is less well known. Data were not available to determine exact mineral compositions (such as the Mg content of calcite) or detailed information on crystal structure (such as the amount of smectite in clays). Information on authigenic phases and more detailed mineralogy can be useful in constraining models of groundwater-rock interactions. A summary of the mineralogy of each geologic unit is provided in the following sections.

4.6.1 Quaternary Alluvium

Quaternary alluvium refers to all post-Santa Fe Group surficial deposits. No information is available from well logs on the mineralogy. From outcrop observations along Tijeras and Coyote arroyos, the alluvium is composed of silts, sands, gravels, and cobbles compositionally similar to the rocks outcropping in the highland areas. Detrital grains are predominantly quartz and feldspar, with abundant rock fragments of limestone, quartzite, chert, granite, and greenstone (a metamorphosed basic igneous rock). Caliche (calcium carbonate formed from evaporation) horizons are common.

4.6.2 Santa Fe Group

The Santa Fe Group is a thick (more than 15,000 feet) sequence of alluvial fan and Rio Grande River deposits containing silt, sand, gravel, and cobbles. Quartz grains, feldspar grains, and clays are abundant throughout the section. Lithic fragments of granite,

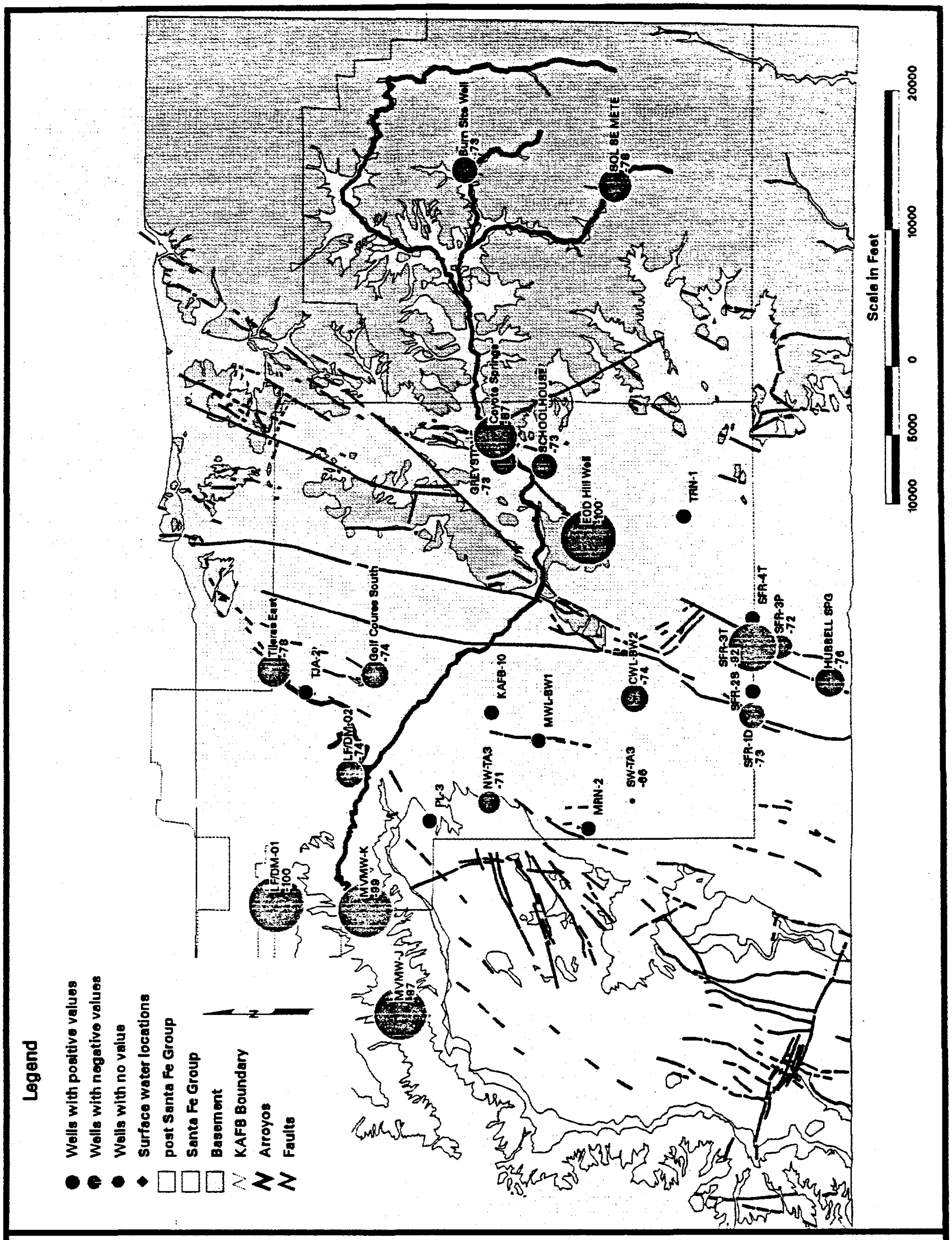


Figure 4-12 : Spot Plot for Delta D (ppt): all MRD wells

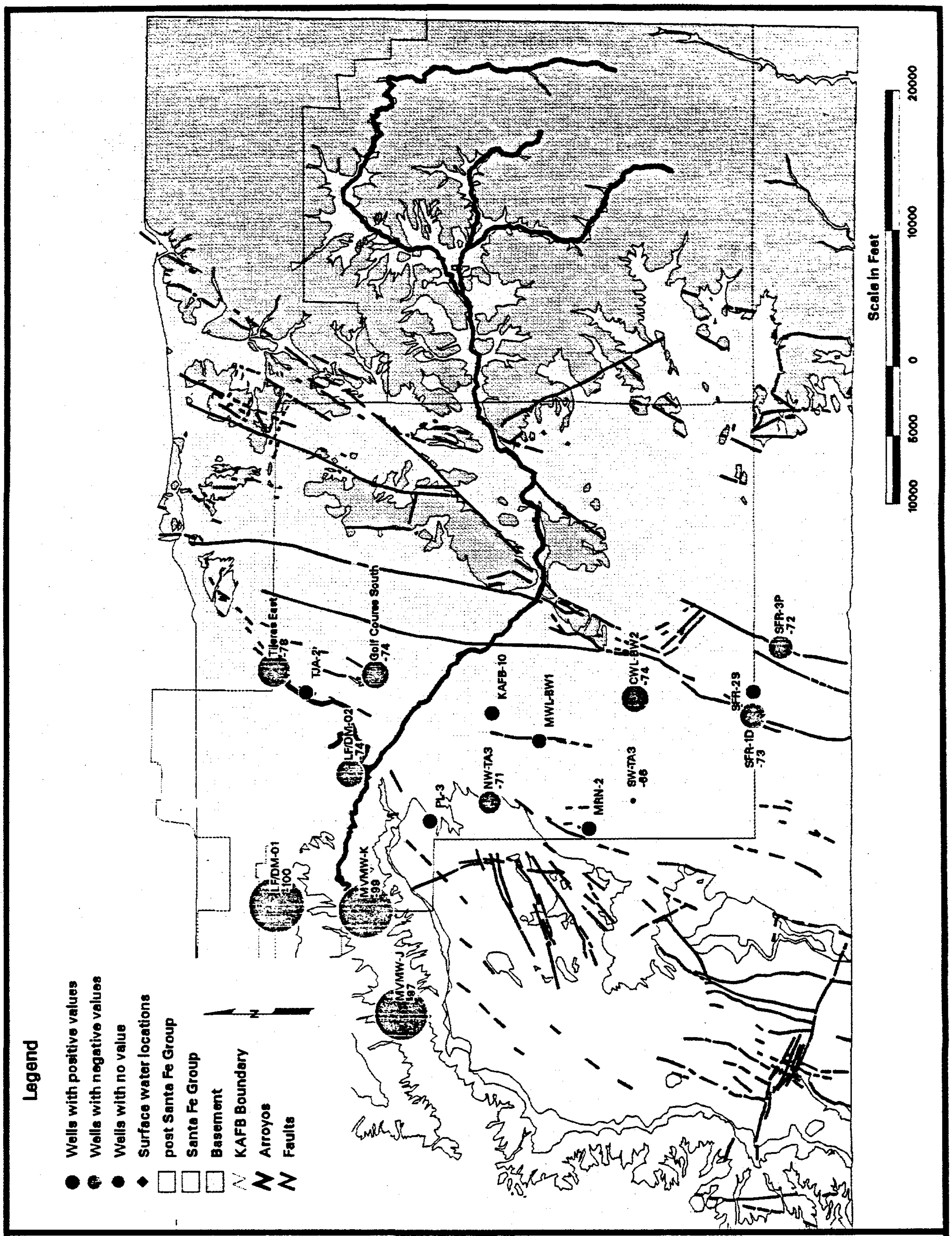


Figure 4-13 : Spot Plot for Delta D (ppt): only those MRD wells screened in the Santa Fe Group gneiss, greenstone, and limestone are common. Caliche zones occur throughout most of the stratigraphic section. Mafic minerals and dolomitic limestone were noted. This section is dominantly oxidized (as evidenced by red to yellow colors), but reduced zones (occasionally with spots of black organics) are present. Plagioclase and K-feldspar are abundant. Volcanic rock fragments (including glass shards and pumice) are abundant in some strata. Authigenic, pore-filling calcite and clay minerals were observed in thin sections.

4.6.3 Lower Tertiary

The lower Tertiary strata are described only in the lithologic log and thin section descriptions for well SFR-3T. At this location, the Lower Tertiary is predominantly green mudstone. Some pyrite and marcasite were observed. One thin section description notes more than 13 percent of the framework grains are volcanic rock fragments. Phyllosilicate cement is abundant; whereas, calcite cement was not documented.

4.6.4 Yeso Formation

The Yeso Formation is described only in well SFR-3T. It is composed mostly of siltstone and mudstone with considerable gypsum. Carbonate minerals and anhydrite are present, and limestone beds are observed in outcrops.

4.6.5 Abo Formation

The Abo Formation is described only in well TRN-1. It is composed of oxidized (red to brown) sandstone, siltstone, and claystone. Sand grains are quartz, feldspar, mica, schist, and limestone. Some caliche is present.

4.6.6 Madera Limestone

The Madera Limestone is dominantly a marine limestone deposit with interbeds of sandstone and conglomerate. Chert is present. Only the EOD Hill well intersects the Madera Limestone; however, it is well exposed in the highlands to the east.

4.6.7 Precambrian Basement

The Precambrian Basement is described in the Burn Site well log as mica, schist, and granite. It is exposed in the highland areas where it has been well described. It contains biotite granite, metarhyolite, quartzite, and greenstone.

5.0 Sandia/KAFB Groundwater Origins and Flow Paths

A major goal of this study was to understand the origin (and thus flowpaths) of the Sandia/KAFB groundwaters. The origin of groundwater at various locations are discussed on the basis of the observations presented in Section 4.0 and the modeling methods described in Section 3.0.

5.1 Groundwater Movement Along Faults: Coyote Springs and EOD Hill

Groundwater seeps at Coyote Springs and well water at EOD Hill have similar chemistries that are much different than all other groundwater studied at Sandia/KAFB. These two locations are elevated in ionic strength, Cl, total inorganic carbon (TIC), Na, Ca, K, and Mg compared with other Sandia/KAFB groundwater (Figure 4-5 and Appendix B). Although Coyote Springs and EOD Hill groundwater are similar to each other when compared with groundwater samples from other Sandia/KAFB wells, they vary from each other markedly in Ca and HCO_3 concentrations (Figure 4-7). Coyote Springs lies on an inferred extension of the northeast-southwest trending fault that passes through EOD Hill well (Figure 4-2).

EOD Hill is oversaturated with CO_2 (pCO_2 greater than 1 atm) and Coyote Springs is slightly undersaturated, as indicated by PHREEQE runs (Table 2-4). Bubbling CO_2 gas at Coyote Springs indicates that the groundwater is oversaturated with CO_2. The apparent discrepancy at Coyote Springs is probably due to the inability of rising, CO_2 exsolving, groundwater to maintain chemical equilibrium. Thus, PHREEQE uses measured parameters to calculate an equilibrium pCO_2 slightly less than 1 atm.

Because most of the difference between Coyote Springs and EOD Hill is the Ca-HCO_3 system, it was hypothesized that Coyote Springs is identical to EOD Hill except that it has exsolved more CO_2 while precipitating calcite. A mass-balance model shows that Coyote Springs groundwater can be produced from EOD Hill groundwater by exsolving 53 millimoles per liter (mmol/L) of CO_2, and precipitating 13 mmol/L of calcite, along with small amounts of other reactions (Table 5-1). Because Cl is considered to be a conservation ion (that is, it does not transfer into solids), the EOD Hill water had to be evaporated by 30 percent to account for the increased Cl concentration at Coyote Springs. Bromide, another conservative ion, is 17 percent higher in concentration at Coyote Springs than at EOD Hill well, supporting the evaporation concept (the differences between 17 and 30 percent evaporation are probably within analytical error).

This model exactly satisfies all mass-balance constraints; however, it is not necessarily valid thermodynamically. EOD Hill is oversaturated with calcite and CO_2, so it is reasonable to expect CO_2 exsolution and calcite precipitation.

Table 5-1. Mass Balance Model for Coyote Springs From EOD Hill

Plausible Phase	Change (mmol/L)[a]
CO_2 gas	-53.4
calcite	-12.6
gypsum	-0.6
Mg/Na exchange	2.2
K-montmorillonite	-1.3
Ca/Na exchange	-5.2
Evaporation factor	30%

[a]"+" indicates phase is added to the water (for exchange reactions, the first element is added and the second is removed from solution); "-" indicates phase is removed from the water.

Using PHREEQE, a reaction-path model was developed to portray the chemical evolution of EOD Hill groundwater as CO_2 is exsolved (Figure 5-1). As CO_2 exsolves from EOD Hill groundwater, calcite precipitates and both Ca and HCO_3 contents decreased (left-hand column of Figure 5-1). Coyote Springs groundwater compares favorable to EOD Hill groundwater after exsolving about 10 to 20 mmol of CO_2 (right-hand column of Figure 5-1). Coyote Springs groundwater is shown at its measured pH of 6.15 and a pH of 6.50 to show the sensitivity of HCO_3 to pH. The relatively small differences in Na, K, Mg, SO_4, and Cl are explained by sampling and analytical uncertainties, as seen in the variations between samplings (Appendix A).

As CO_2-charged (CO_2 greater than 1 atm) groundwater rises along the fault at Coyote Springs, the hydrostatic pressure decreases and CO_2 exsolves. The modeling presented here indicates that the ancestral water could be identical to the water sampled at EOD Hill; or EOD Hill and Coyote Springs groundwaters could be evolved products from a common ancestral water body. That these two groundwaters both have anomalous concentrations of many salts and occur adjacent to basin faults, together with the geochemical models, suggests that deep groundwater is upwelling along these faults. The ultimate source of this groundwater cannot be determined from these data. The higher salinities suggest a component of deep formation fluid.

By starting with EOD Hill groundwater composition and progressively exsolving CO_2, it is shown that a thermodynamically valid path exists to obtain Coyote Springs groundwater. Mineral saturation indices (SIs) are monitored along the reaction path to check that no violations exist (for example, the failure to allow a mineral to precipitate). SIs for the reaction-path model are shown in Figure 5-2. The first reaction step has a sharper change because it includes the equilibration of EOD Hill groundwater with calcite (it was initially oversaturated). As CO_2 is exsolved, pCO_2 drops; after about 400 mg/L of CO_2, it is below 1 atm. CO_2 would continue to leave the groundwater at this stage due to diffusion because atmospheric pCO_2 is much lower (about $10^{-3.5}$ atm);

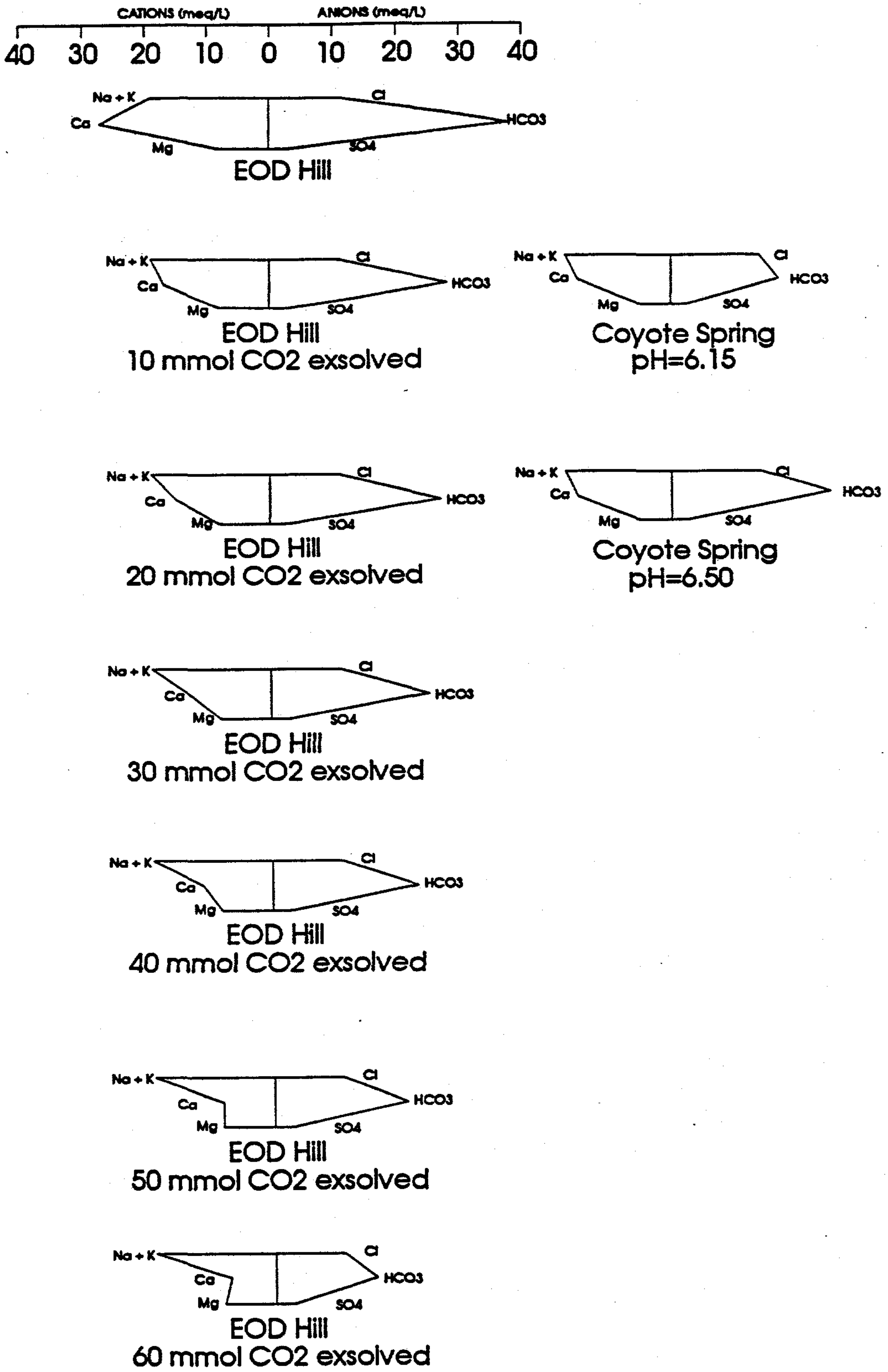


Figure 5-1. Stiff Diagrams Showing Reaction Paths as CO_2 Exsolves from EOD Hill Water and Comparison to Coyote Springs at its Measured pH (6.15) and at pH 6.50

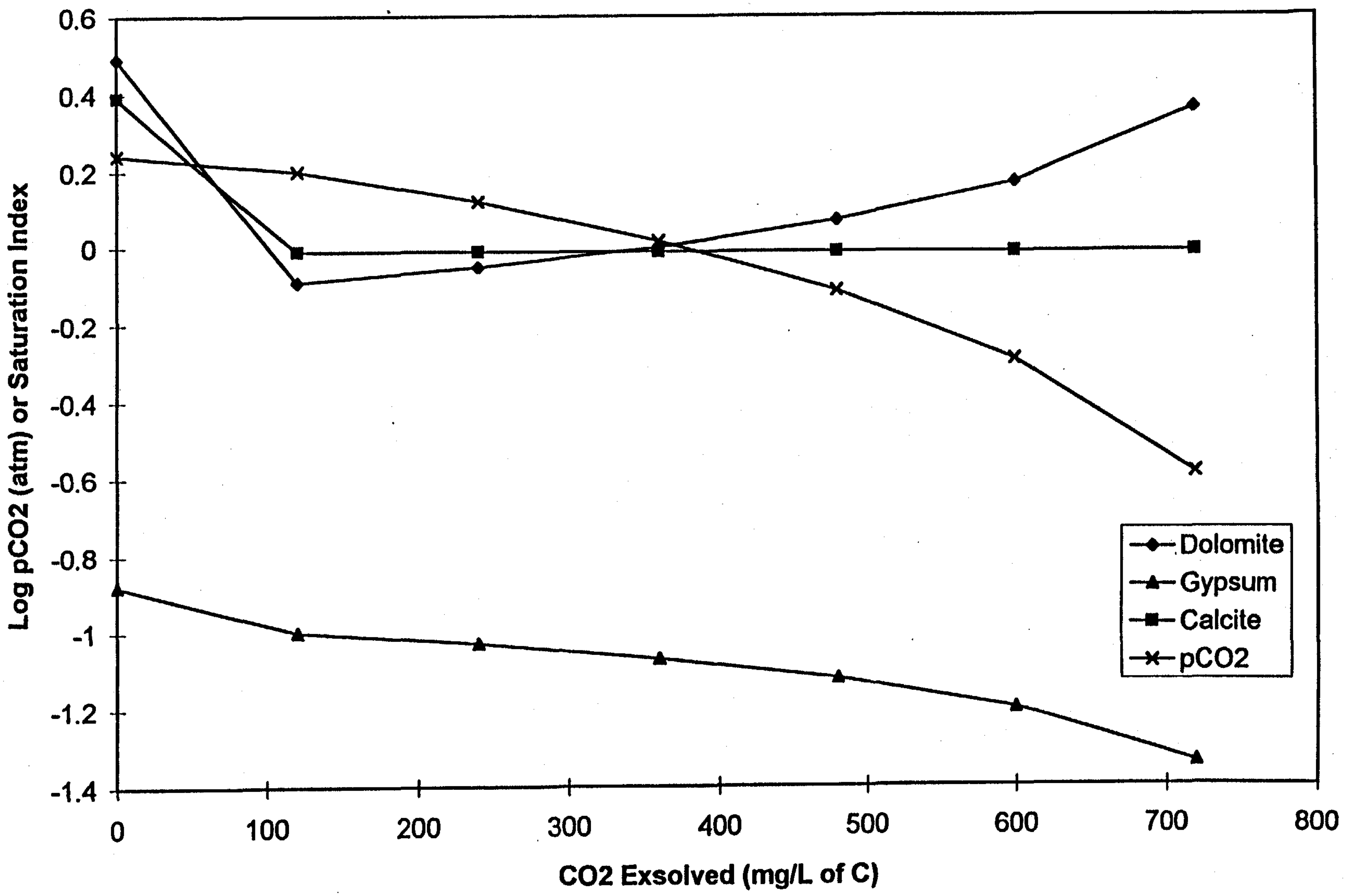


Figure 5-2. Mineral Saturation Indices and CO_2 Partial Pressures During Exsolution of CO_2 from EOD Hill Water

however, the rate would be slower. Gypsum is undersaturated throughout the simulation and would not precipitate. Dolomite becomes undersaturated after the first reaction step and then becomes oversaturated as the reaction proceeds. At the low temperatures of these groundwaters, dolomite is not likely to precipitate and, thus, does not violate thermodynamic constraints. Calcite stays at saturation throughout the simulation as a condition of the model.

Besides having anomalously high concentrations of most major ions, EOD Hill and Coyote Springs also have depleted signatures for $\delta^{18}O$ and δD. These chemical distinctions from surrounding wells suggest that the groundwater at EOD Hill/Coyote Springs has a different source. The chemical model presented above suggests that EOD Hill and Coyote Springs groundwater are from the same source; most of the chemical variation between them can be explained by CO_2 releases at Coyote Springs.

The difference in Cl concentration between EOD Hill and Coyote Springs is explained by evaporation at Coyote Springs; the δD variation can also be explained by evaporation of a similar magnitude. On a plot that compares δD values with $\delta^{18}O$ values, Coyote Springs groundwater lies on a line of slope 6 from EOD Hill groundwater (Figure 4-11). If evaporation followed a simple Rayleigh distillation, evaporated waters would lie on the MWL with a slope of 8. Data from naturally evaporated waters and experimental evidence indicate, however, that evaporated water becomes heavier in $\delta^{18}O$ relative to δD; slopes range from about 4 to 6 (Craig et al. 1963). The slope of 6 for the Coyote Springs groundwater is in agreement with this range, suggesting that evaporation of about 20 percent could account for the δD - $\delta^{18}O$ evolution from EOD Hill groundwater. Evaporation could occur in the pool from which Coyote Springs is sampled, perhaps enhanced by the effervescing CO_2 gas.

Groundwater sampled from two shallow alluvial wells (Greystone and Schoolhouse) near EOD Hill/Coyote Springs both have δD values of -73‰ (Figure 4-12). Sol se Mete Spring farther to the east has a δD value of -78‰. These values are all within the range (-70 to -83‰) depicted by Yapp (1985) for recharge from Sandia/NM and Manzano Mountains and suggests that these groundwaters represent shallow infiltration. The δD of rainfall is dependent on latitude, climate (temperature and amount of precipitation), and elevation (Dansgaard 1964). Elevation should increase the δD value; however, the value for Sol se Mete Spring suggests that elevation within the project area has a minimal effect.

EOD Hill and Coyote Springs have δD values (-100 and -87‰) which are significantly depleted and, thus, are unlikely to be related to infiltration. The δD values coupled with the more saline chemistry suggests that these two groundwaters originate at depth. Chemical and isotopic data from deep basins are limited; however, it is useful to speculate on possible origins of a δD depleted deep water source.

Yapp (1985) identified depleted δD signatures in the deeper horizons of the Santa Fe Group in the Albuquqerque Basin and proposed that this was old water that had been introduced from the Rio Grande River during a time when climatic differences produces δD depleted precipitation. It is common for δD and salinity to increase with depth in a basin. A well-studied example is the Milk River aquifer in Alberta, Canada. The δD data from this aquifer show a distinct trend of δD depletion with depth. The cause of the δD depletion is controversial, having been explained by dispersive mixing with connate water (Schwartz and Muehlenbachs 1979), membrane filtration (Phillips et al 1986), and diffusion from shales (Hendry and Schwartz 1988).

These observations suggest that it is reasonable to expect depleted δD values in deeper basin groundwaters.

5.2 Midbasin Santa Fe Group Groundwater (CWL–BW2 and MWL–BW1)

Chloride concentrations in the Santa Fe Group groundwater appear to decrease westerly away from the basin boundary faults (Figure 4–6 and Figure 4–2). Other dissolved ions (Na, Ca, TIC, Br, and F) also appear to show this spatial distribution (Appendix B). These distributions suggest that high-salinity groundwater such as that present at EOD Hill may be entering the basin near the eastern basin boundary.

Examination of the major ion chemistry indicates that with the exception of TIC, dissolved major ions in CWL–BW2 are consistent with dilution factors between 2 and 6, and almost all are 3 to 4 (Table 5–2). A mass-balance model using NETPATH shows the extent of gas and mineral phase reactions required if EOD Hill groundwater is mixed with pure water to produce CWL–BW2 groundwater (Table 5–3). A relatively large dilution (67-percent pure water) is required and a large amount of CO_2 gas must be lost. The dilution will be larger if the dilute water were not pure water, but rather had some ions in it.

Models such as these do not identify the source of the dilute (pure) water. Dilute water may come from vertical infiltration or recharge from Coyote arroyo. If groundwater at MVMW-K (a well drilled on the Tijeras arroyo) is used to simulate the dilute groundwater, the results are similar to using pure water (Table 5–3).

CWL–BW2 is the closest well to the basin boundary. Unfortunately, this well is screened over a much thicker and deeper interval (490–980 feet) than other Santa Fe Group wells except KAFB–10. It is possible that the CWL–BW2 groundwater signature is influenced by deeper saline horizons. MWL–BW1 (also completed in the Santa Fe Group) samples are shallower (452–472 feet) and are more dilute than CWL–BW2 (see the ionic strength spot plot in Appendix B). MWL–BW1 is farther out in the basin than CWL–BW2, and flow directions (Figure 4–3) indicate that this area is influenced by groundwater flowing westerly. Mass-balance models for the evolution of MWL–BW1 both from CWL–BW2 and from EOD Hill groundwater are in Table 5–4. Both models indicate a high degree of dilution to obtain the relatively low ionic concentrations at

MWL-BW1. As with the previous models, use of a dilute groundwater such as MVMW-K instead of pure water would not significantly change the model results.

Table 5-2. Comparison of EOD Hill and CWL-BW2 Groundwater Chemistries

Component	EOD Hill	CWL-BW2	Dilution Factor
Ca	540	130	4
Na	410	87	5
K	38	7	6
Mg	100	30	3
Cl	390	130	3
SO_4	140	77	2
TIC	1175	114	10
Ionic Strength	0.067	0.017	4
pH	6.07	6.85	-

Table 5-3. NETPATH Models: Mixing of EOD Hill Groundwater with Dilute Water (pure water or MVMW-K groundwater) to Produce CWL-BW2 Groundwater

Plausible Phases	Mass Transfer[a]	
	Pure Water (mmol/L)	MVMW-K Groundwater (mmol/L)
CO_2 gas	-27.5	-25.2
Calcite	-2.8	-3.5
Gypsum	+0.3	+0.1
K-montmorillonite	-0.5	-0.5
Na/Ca exchange	+1.2	+1.5
Mg/Na exchange	+0.1	+0.2
Percent of dilute water	67%	69%
Percent of EOD water	33%	31%

[a] "+" indicates phase is added to the water (for exchange reactions, the first element is added and the second is removed from solution); "-" indicates phase is removed from the water.

Table 5–4. NETPATH Models: Mixing of EOD Hill or CWL–BW2 Groundwater with Pure Water to Produce MWL–BW1 Groundwater

Plausible Phases	Mass Transfer[a] EOD Hill (mmol/L)	CWL-BW2 (mmol/L)
CO_2 gas	-6.7	-1.3
Calcite	+1.4	+1.9
Gypsum	+0.3	+0.3
K-montmorillonite	+0.1	+0.2
Ca/Na exchange	+1.2	+1.4
Mg/Na exchange	-0.6	-0.6
Percent of EOD or CWL-BW2	7%	20%
Percent of pure water	93%	80%

[a] "+" indicates phase is added to the water (for exchange reactions, the first element is added and the second is removed from solution); "-" indicates phase is removed from the water.

These results indicate that a small contribution of groundwater in the Santa Fe Group may have come from saline fluids migrating along the basin boundary faults. This saline fluid is a minor component, however, compared to a more dilute fluid that dominates the Santa Fe Group groundwater system. Geochemical data are insufficient to determine the exact origin (arroyo infiltration, inter-arroyo infiltration, Rio Grande, or low-salinity mountain discharge) of this dilute fluid. Recent measurements by Sandia/NM indicate that arroyo recharge is about 1/3 or less of mountain-front recharge.

5.3 Groundwater at South Fence Road Wells

5.3.1 Santa Fe Group Groundwater Chemistry

The similarity of Santa Fe Group groundwater chemistry between wells SFR–1, SFR–2, and SFR–3P indicates a common origin (Figure 4–9). Elevated Cl concentrations relative to other Santa Fe Group wells (Figure 4–6) suggest an influence from the high-salinity fluids moving along the basin faults. The amount of dilution required to produce SFR–3P groundwater from EOD Hill (used to simulate the high-salinity, fault-related fluid) groundwater is presented in Table 5–5.

The Ca, Na, Mg, and Cl in SFR–3P could be the result of mixing of a saline fluid, such as EOD Hill groundwater, with a dilute fluid with dilution factors of 3 to 5. The lower dilution factor for SO_4 suggests an influx of SO_4 from the high-SO_4 groundwaters observed in SFR–3T and SFR–4T. The high TIC dilution factor suggests CO_2 exsolution or calcite precipitation.

Table 5-5. Dilution Factors for Major Ions to Produce SFR-3P From EOD Hill Groundwater

Component	SFR-3P (mg/L)	EOD (mg/L)	Dilution Factor [a]
Ca	120	540	5
Na	87	410	5
K	4.6	38	8
Mg	28	100	4
TIC	100	1175	12
SO_4	94	140	2
Cl	140	390	3
pH	6.85	6.07	

[a] EOD divided by SFR-3P.

NETPATH was used to examine the results of mixing three different types of groundwater (EOD Hill, SFR-3T, and pure water) to produce the groundwater composition of SFR-3P (Table 5-6).

Table 5-6. NETPATH Results of Mixing Groundwater from EOD Hill, SFR-3T, and Pure Water to Produce SFR-3P Groundwater

Plausible Phase	Mass Transfer (mmol/L) [a]
CO_2 gas	-28.9
Calcite	-3.9
Gypsum	+0.0
K-montmorillonite	-0.7
Mg/Na exchange	+0.3
Na/Ca exchange	+1.8
Water Type	**Amount %**
EOD Hill	+36
SFR-3T	+2
Pure Water	+62

[a] "+" indicates phase is added to the water (for exchange reactions, the first element is added and the second is removed from solution); "-" indicates phase is removed from the water.

This model indicates that SFR-3P groundwater can be produced from 62-percent dilute water (simulated by pure water), 36-percent EOD Hill water (simulating the saline fault-related water), and 2-percent SFR-3T (simulating high-SO_4 water from the footwall of the fault). The dominant reaction is the release of TIC via CO_2. As with the previous models that simulate the Santa Fe Group waters, a dilute groundwater is required. This dilute groundwater is likely to have its origin from infiltration of precipitation. Geochemical data are not sufficient to determine if this water infiltrates in the arroyos or the inter-arroyo areas.

5.3.2 Lower Tertiary Groundwater in the Footwall

Two wells (SFR-3T and SFR-4T) are screened in the Lower Tertiary unit along South Fence Road. The groundwater compositions of these two wells suggest that groundwater initially saturated with gypsum has migrated through the Lower Tertiary unit and exchanged Ca for Na. SFR-3T and SFR-4T have nearly equivalent SO_4 concentrations; however, SFR-4T has a higher concentration of Na relative to Ca (Table 5-7). The SI for gypsum (-0.049) in the SFR-3T well indicates the presence of gypsum; however, well SFR-4T is significantly undersaturated (SI = -0.956) with gypsum (Table 2-4). If groundwater similar to SFR-3T contacts Na-rich exchangeable clay minerals, Ca will exchange with Na and produce a composition similar to that observed in SFR-4T.

Table 5-7. Composition of SFR-3T Before and After Computed Reactions Compared to SFR-4T

Component	mmol/L		
	SFR-3T	SFR-3T After Reaction[a]	SFR-4T
Ca	11.26	2.70	1.43
Na	21.82	50.74	52.38
K	0.14	0.06	0.06
Mg	1.69	0.14	0.14
Cl	1.33	5.07	5.09
HCO_3	0.34	5.51	2.30
SO_4	22.98	22.98	19.85
pH	7.45	7.43	7.57

[a] Calculated water composition after reacting 11 mmol/L of the reaction: (in mmol/L) -1.000 Ca, 2.629 Na, -0.141 Mg, -0.007 K, and 0.340 Cl. Calculation includes the equilibration with calcite and $pCO_2 = 10^{-2.00}$ atm.

A NETPATH calculation supports the concept that Ca has exchanged for Na to form SFR-4T groundwater from SFR-3T groundwater (Table 5-8). In the model, Ca/Na exchange is the dominant factor. Moderate amounts of calcite and halite dissolution, gypsum precipitation, CO_2 loss, and Mg/Na exchange are also required.

Table 5–8. NETPATH Model To Produce SFR–4T from SFR–3T Groundwater

Plausible Phase	Mass Transfer (mmol/L)*
CO_2 gas	-3.2
Calcite	+5.1
Gypsum	-3.1
Halite	+3.8
K-montmorillonite	-0.22
Mg/Na exchange	+1.55
Ca/Na exchange	+11.85

*"+" indicates phase is added to the water (for exchange reactions, the first element is added and the second is removed from solution); "-" indicates phase is removed from the water.

The results of the NETPATH model were used to formulate a reaction-path model. In this model, Ca, Mg, and K are exchanged for Na, and Cl is balanced by the addition of halite. This "reaction" (-1.000 Ca, -0.141 Mg, -0.007 K, 0.340 Cl, and 2.629 Na; in mmol/L) is added in steps to the SFR–3T water while maintaining equilibrium with calcite and pCO_2 of $10^{-2.0}$ atm. The cation ratios were determined by examining the NETPATH results (Table 5–8). The pCO_2 of $10^{-2.0}$ atm is a reasonable value for a subsurface environment and is consistent with many of the values for the Sandia/KAFB site (Table 2–4).

The reaction was added in steps up to 11.0 mmol/L. The results of adding 1.8, 5.5, and 11.0 mmols of reaction are shown as Stiff diagrams in Figure 5–3, and the results of the 11.0 mmol step are listed in Table 5–7. The results of the 11 mmol step are a reasonable match to the SFR–4T composition (Figure 5–3 and Table 5–7). The pH of the simulation is 7.43 which also compares favorably with the pH of 7.57 measured in SFR–4T.

Saturation indices for common minerals are shown as a function of reaction progress in Figure 5–4. Calcite remains at saturation as a condition of the model. Since gypsum was only slightly oversaturated in SFR–3T, it was allowed to start out oversaturated. Gypsum equilibrium was not set as a condition in the model because gypsum was observed only in the area of the initial solution (Yeso Formation or in the fault) and not in the Lower Tertiary unit. All other minerals were undersaturated throughout the simulation.

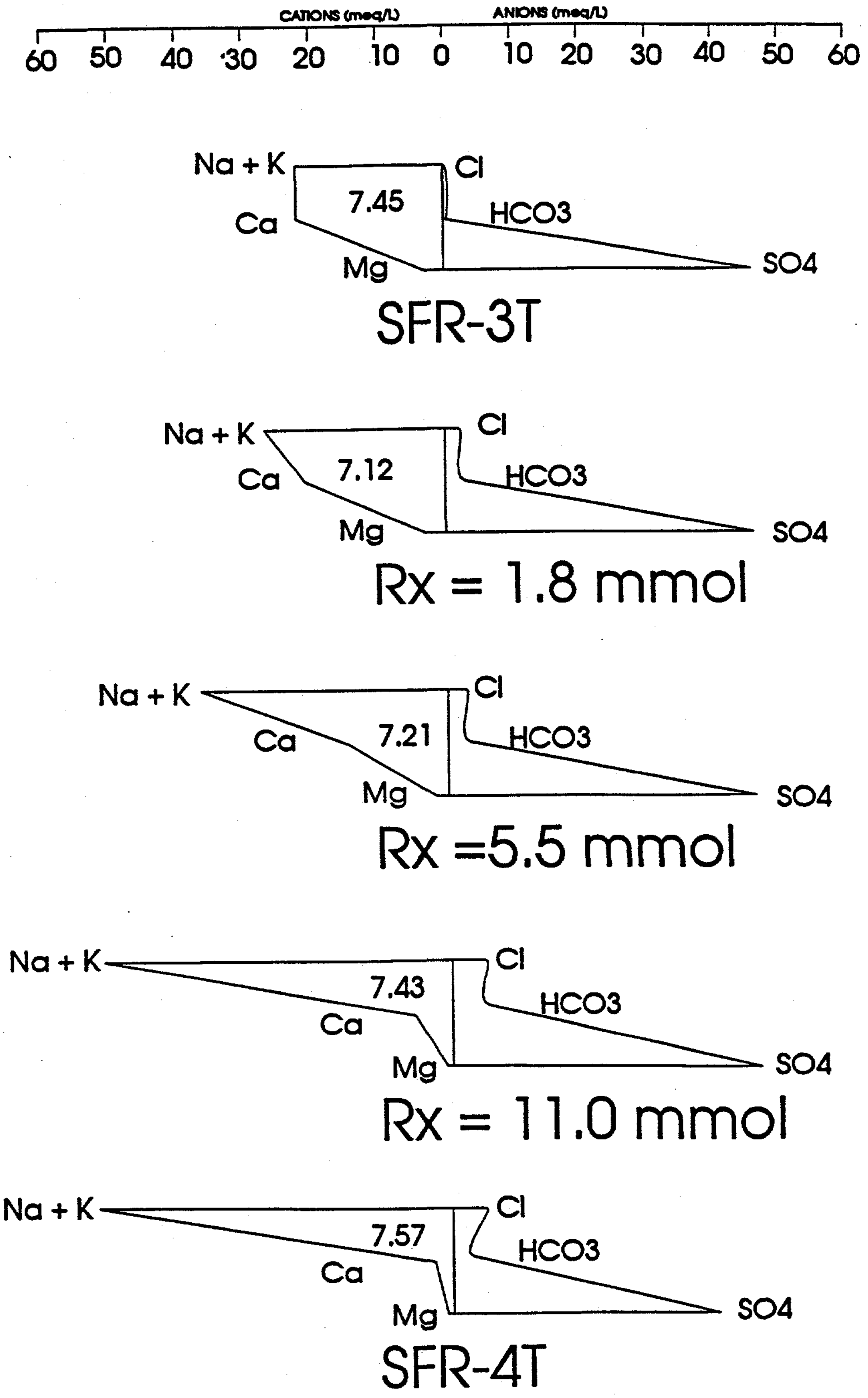


Figure 5-3. Stiff Diagrams Showing the Chemical Evolution of SFR-3T Groundwater as 1.8, 5.5, and 11.0 mmol of a Reaction are Added, Compared to SFR-4T

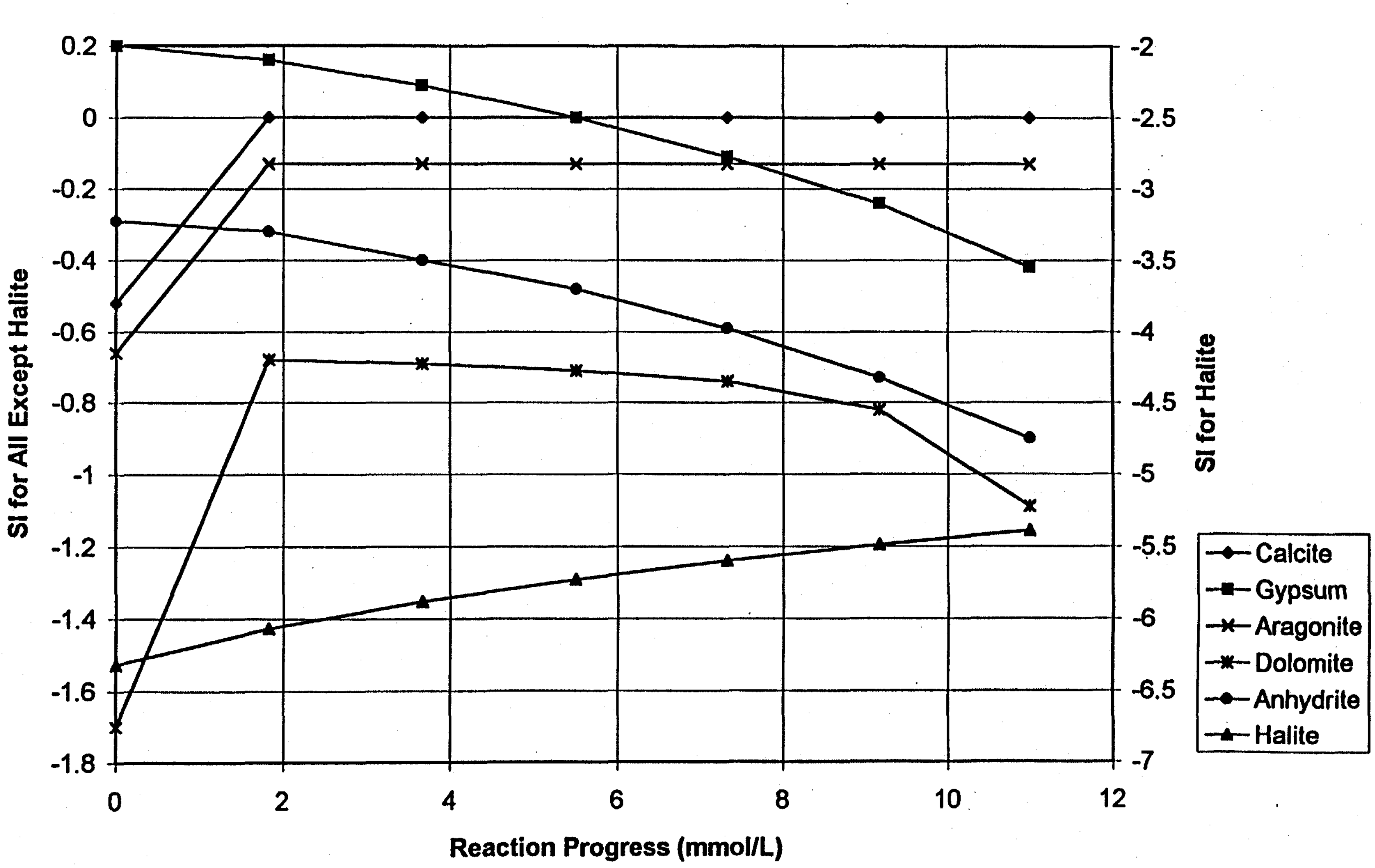


Figure 5–4. Saturation Indices for Common Minerals During Reaction of SFR–3T (reaction progress refers to amount of reaction added)

Note that the reaction-path model simulates all the cations by cation-exchange reactions whereas the NETPATH simulation used precipitation of K-montmorillonite to account for the K loss. Either of these clay mineral reactions is permissible given the lack of any data on the clay mineral composition of the subsurface. The Lower Tertiary unit is composed largely of mudstone and siltstone which is likely to contain abundant exchangeable clay minerals.

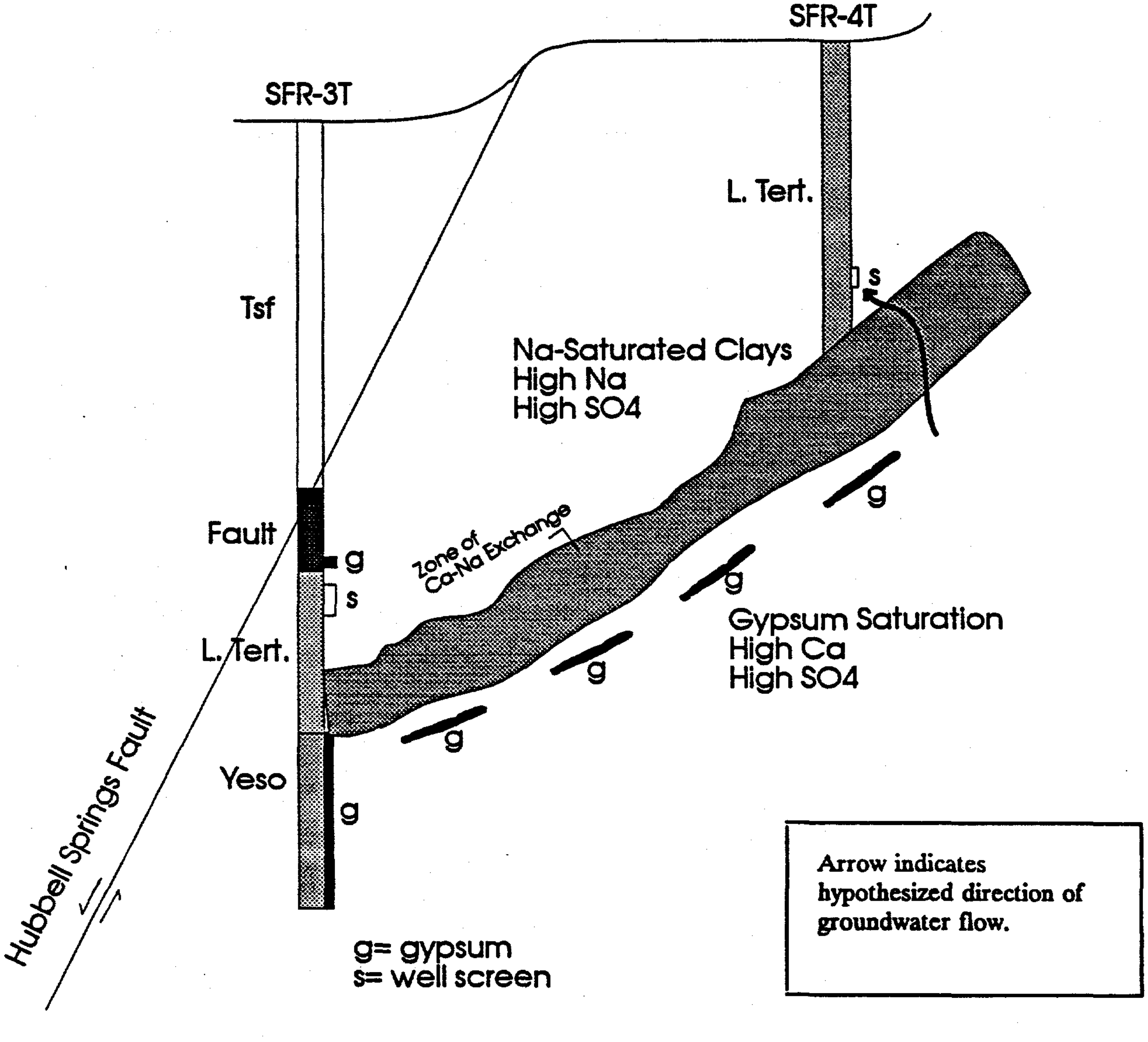
In summary, the reaction-path model shows that if SFR-3T groundwater were to flow through a reactive zone containing calcite, Na-rich exchangeable clays, and a small amount of halite, a groundwater similar in composition to SFR-4T would evolve (Figure 5-5).

5.4 Groundwater in the Tijeras Arroyo Area

The NPN anomaly at over 400 feet beneath the Tijeras Arroyo Golf Course (Figure 4-10) suggests vertically downward infiltration. Fertilizers applied to the golf course are a common source of nitrogen. The heavy irrigation (equivalent to about 48 inches per year) and standing water greatly enhance infiltration. The composition of the groundwater in the Golf Course South well is likely a reflection of the composition of the irrigation water after it has reacted with the Santa Fe Group aquifer.

The anomalously high cation/anion charge imbalance (Table 2-4) in groundwater from the Golf Course South well suggests that a major anion was not included in the chemical analyses. If the missing anion were phosphate or an organic anion common to fertilizer, this would support the concept of vertical migration to depths of more than 400 feet.

A NETPATH model indicates that the composition of Golf Course South well groundwater will be produced if pure water were to dissolve small amounts of calcite, gypsum, and halite along with some CO_2 release and cation exchanges. The Cl in the water more likely results from the initial composition (perhaps with some evaporation) of the irrigation water rather than from the dissolution of halite. The model assumes that the irrigation water is dilute (pure water). Therefore, the chemical reactions presented in Table 5-9 can be considered maximums. All the mass transfer in Table 5-9 is relatively minor (and would decrease if significant dissolved ions were in the initial water) and, thus, the model provides one reasonable explanation for the origin of the Golf Course South groundwater.



Arrow indicates hypothesized direction of groundwater flow.

Figure 5-5. Schematic Diagram Showing Origin of SFR-4T Water from SFR-3T Water (High SO_4, High Ca)

Table 5-9. NETPATH Calculated Chemical Interactions to Produce Golf Course South Groundwater from Pure Water

Phase	Mass Transfer (mmol/L)*
CO_2 gas	-1.42
Calcite	+1.95
Gypsum	+0.68
K-montmorillonite	+0.19
Na/Mg exchange	-0.70
Ca/Na exchange	+0.48
halite (NaCl)	+1.35

*"+" indicates phase is added to the water (for exchange reactions, the first element is added and the second is removed from solution); "-" indicates phase is removed from the water.

6.0 Conclusions and Recommendations

Mass-balance and reaction-path models were used to help understand the chemical evolution of groundwater at the Sandia/KAFB site. The geochemical models showed that the geochemistry of the groundwater is consistent with existing conceptual models of groundwater flow. Because the chemistry of the solid components is not completely known, the geochemical models have few constraints and, thus, multiple models are possible.

Spatial relationships of major ions in groundwater at the Sandia/KAFB site offer insight into the origin of the groundwater. In the Santa Fe Group, Cl and other ion concentrations decrease away from the basin-boundary faults to the western portion of the basin. Higher concentrations of Cl and other ions are found in groundwater directly associated with the faults (EOD Hill and Coyote Springs). The chemical signature of the fault-related groundwater suggests a deep origin.

Mass-balance models were developed that are consistent with mixing of the high-salinity, fault-related groundwater with a dilute groundwater to produce the Santa Fe Group groundwater near the boundary faults. About 33-percent high-salinity fluid was required. The origin of the dilute groundwater is not constrained by existing geochemical data.

Some of the groundwater in the footwall near South Fence Road is high in Ca and SO_4 due to equilibration with gypsum. This water has exchanged Ca for Na as it migrated through Na-rich clays, resulting in a Na–SO_4 enriched groundwater. This Na–SO_4 water makes up less than 2 percent of the Santa Fe Group groundwater in the South Fence Road wells.

To gather enough geochemical information on the subsurface to produce a reasonably unique model capable of defining groundwater flow paths and recharge areas would be a monumental task. It is recommended that resources would be better spent drilling additional wells for geohydrologic testing and using environmental tracers (e.g., ^{3}H, ^{36}Cl, Br, ^{14}C) to obtain information on groundwater flow. Artificially induced tracers could be used in areas where high flow rates are expected.

7.0 References

Anderholm, S.K., 1988. "Ground-Water Geochemistry of the Albuquerque Basin, Central New Mexico," *U.S. Geol. Survey Water-Resources Investigations Report*, 86–4094.

Craig, H., 1961. "Isotopic Variations in Meteoric Waters," *Science*, Vol. 133, pp. 1702–1703.

Craig H., L.I. Gordon, and Y. Horibe, 1963. "Isotopic Exchange Effects in the Evaporation of Water," *Jour. Geophys. Research*, Vol. 68.

Dansgaard, W., 1964. "Stable Isotopes in Precipitation," *Tellus*, Vol. 16, pp. 436–468.

Garrels, R.M., and F.T. MacKenzie, 1967. "Origin of the Chemical Composition of Some Springs and Lakes in Equilibrium Concepts in Natural Water Systems," *Amer. Chem. Soc. Adv. Chem. Ser.*, No. 67, pp. 222–242.

Helgeson, H.C., 1968. "Evaluation of Irreversible Reactions in Geochemical Processes Involving Minerals and Aqueous Solutions—I. Thermodynamic Relations," *Geochemical et Cosmochemical Acta*, Vol. 32, pp. 853–877.

Hendry, M.J. and F.W. Schwartz, 1988. "An Alternative View on the Origin of Chemical and Isotopic Patterns in Groundwater from the Milk River Aquifer, Canada," *Water Resources Research*, Vol. 24, pp. 1747–1763.

__________, 1979. "Mass Transfer Among Minerals and Hydrothermal Solutions," in *Geochemistry of Hydrothermal Ore Deposits*, Second Edition, ed. by H. L. Barnes, John Wiley & Sons, New York, pp. 568–610.

Parkhurst, D. L., D.C. Thorstenson, and L.N. Plummer, 1980. "PHREEQE—A Computer Program for Geochemical Calculations," *U.S. Geol. Survey Water-Resources Investigations Report*, 80–96.

__________, 1982. "BALANCE—A Computer Program for Calculating Mass Transfer for Geochemical Reactions in Ground Water," *U.S. Geol. Survey Water-Resources Investigations Report*, 82–14.

Phillips, F.M., H.W. Bentley, S.N. Davis, D. Elmore, and G.B. Swanick, 1986. "Chlorine 36 Dating of Very Old Groundwater 2. Milk River Aquifer, Alberta, Canada," *Water Resources Research*, Vol. 22, pp. 2003–2016.

Plummer, L.N., E.C. Prestemon, and D.L. Parkhurst, 1991. "An Interactive Code (NETPATH) for Modeling NET Geochemical Reactions Along a Flow Path," *U.S. Geol. Survey Water-Resources Investigations Report*, 91–4078.

Plummer, L.N., D.L. Parkhurst, and D.C. Thorstenson, 1983. "Development of Reaction Models for Ground-Water Systems," *Geochemical et Cosmochemical Acta*, Vol. 47, pp. 665–686.

Sandia National Laboratories/New Mexico (Sandia/NM), 1993. *Sandia National Laboratories Groundwater Monitoring Program Calendar Year 1992, Annual Report*, Sandia National Laboratories/New Mexico, Albuquerque.

__________, 1994a. *Sandia National Laboratories, Groundwater Protection Program, Calendar Year 1993 Annual Groundwater Monitoring Report*, Sandia National Laboratories/New Mexico, Albuquerque.

__________, 1994b. *Sandia National Laboratories Site-Wide Hydrogeologic Characterization Project, Calendar Year 1993 Annual Report*, Sandia National Laboratories/New Mexico, Albuquerque.

__________, 1995. *Sandia National Laboratories, Groundwater Protection Program Calendar Year 1994 Annual Groundwater Monitoring Report*, Sandia National Laboratories/New Mexico, Albuquerque.

Schwartz, F.W., and K. Muehlenbachs, 1979. "Isotope and Ion Geochemistry of Groundwaters in the Milk River Aquifer, Alberta," *Water Resources Research*, Vol. 15, pp. 259–268.

Yapp, C. J., 1985. "D/H Variations of Meteoric Waters in Albuquerque, New Mexico, U.S.A.," *Journal of Hydrology*, Vol. 76, pp. 63–84.

Appendix A

Geochemical Database (sand.dat) Used in this Study

(a negative number indicates less than)

References for this database are Sandia/NM 1993, 1994a, and 1995.

```
sand.dat
This file includes the entire database put together by Stan Morrison
for the Geochemistry Site-Wide Study. It does not exclude any of the
analyses. sand.1 etc are amended databases that exclude some data.
Backup copy is store in /b

HISTORY:
3/1/95-3/7/95  First compilation of data. Includes Alk, Br,
   Cl, F, pH, SO4, Ca, Fe, Mg, K, NPN, and NO3.
3/7/95 Replaced all non-detects with negative numbers.
3/7/95 Recalculated 1992 alk data as mg/L CaCO3 and entered.
3/8/95 Changed all alkalinities to field values.
3/8/95 Entered turbidity data (only 1994 available).
3/10/95 All entries checked for accurracy by Renee Rodgers.
3/10/95 pH entries changed from lab values to field values,
  the last entry is the one that is used. Franz Lauffer said
  that this last entry is the one that correlates to the
  field alkalinity measurement.
3/23/95 Entered Ionic Str (PHREEQE), Carbon (PHREEQE),Cat/Anion (PHREEQE),
  SI Calcite (PHREEQE), SI Gypsum (PHREEQE), and PCO2, atm (PHREEQE) for
  the "most representative" data.
5/1/95 Revised SI gypsum by subtracting .246 from the previous numbers to
  adjust from log K = -4.848 to -4.602 which fits experimental data better
5/8/95 Added the Silica data
6/13/95 Added new well data: SFR-4T, PL-3, TRN-1, MRN-2, TJA-2, and PL-2.
6/13/95 Added D/H and 18O/16O data
7/11/95 Corrected sand.dat following QA checks by Linda Gray. Only 2
        additions to D/H and 18O/16O were required plus rounding.

NOTES:
All are in mg/L except pH (standard pH units), alkalinity (mg/L of CaCO3),
   and turbidity (NTU units).
Non-detects are listed as negative numbers
Alkalinities are field measurements as far as can be determined.
A blank line indicates that no data are available.


          Burn Site Spring
      ANALYTE               1994/06/00 0000/00/00 0000/00/00 0000/00/00 0000/00/00
  1 Alkalinity (field)        355.000
  2 Bromide                      .520
  3 Chloride (Cl)              38.000
  4 Fluoride (F) (Dissol          .800
  5 pH (field)                  7.400
  6 Sulfate (SO4)              89.000
  7 Calcium (Ca) (Dissol      760.000
  8 Iron (Fe) (Dissolved       76.000
  9 Magnesium (Mg) (Diss       69.000
 10 Potassium (K) (Disso       18.000
 11 Sodium (Na) (Dissolv       29.000
 12 Nitrogen (NPN)               .120
 13 Nitrate
 14 Turbidity (NTU)
 15 Ionic Str (PHREEQE)
 16 Carbon (PHREEQE)
 17 Cat/Anion (PHREEQE)
 18 SI Calcite (PHREEQE)
 19 SI Gypsum (PHREEQE)
 20 PCO2, atm (PHREEQE)
 21 Silica (mg/L)             130.000
```

22 D/H (ppt)	
23 180/160 (ppt)	

Burn Site Well

ANALYTE	1992/01/09	1992/07/22	1993/04/00	1993/07/00	1993/09/00
1 Alkalinity (field)	212.000	199.000	256.000	228.000	198.000
2 Bromide	.700	.400	.710	.720	.800
3 Chloride (Cl)	62.200	32.200	52.000	59.000	60.000
4 Fluoride (F) (Dissol	.900	.400	1.000	.900	1.200
5 pH (field)	7.170	6.690	6.890	5.840	7.150
6 Sulfate (SO4)	221.500	101.500	130.000	-20.000	140.000
7 Calcium (Ca) (Dissol	104.600	75.700	86.000	100.000	96.000
8 Iron (Fe) (Dissolved			.020	-.020	.040
9 Magnesium (Mg) (Diss	32.100	32.100	-.200	38.000	38.000
10 Potassium (K) (Disso	2.600	4.600	4.200	3.800	3.700
11 Sodium (Na) (Dissolv	34.200	26.100	24.000	-.200	26.000
12 Nitrogen (NPN)			1.000	1.000	3.700
13 Nitrate	29.800	3.700			
14 Turbidity (NTU)					
15 Ionic Str (PHREEQE)					
16 Carbon (PHREEQE)					
17 Cat/Anion (PHREEQE)					
18 SI Calcite (PHREEQE)					
19 SI Gypsum (PHREEQE)					
20 PCO2, atm (PHREEQE)					
21 Silica (mg/L)					
22 D/H (ppt)					
23 180/160 (ppt)					

Burn Site Well

ANALYTE	1993/12/00	1994/03/00	1994/06/00	1994/09/00	0000/00/00
1 Alkalinity (field)	197.000	173.000	210.000	220.000	
2 Bromide	.700	.700	.820	.810	
3 Chloride (Cl)	53.000	45.000	60.000	56.000	
4 Fluoride (F) (Dissol	1.000	1.000	.800	.900	
5 pH (field)	7.350	7.080	7.410	6.800	
6 Sulfate (SO4)	150.000	150.000	150.000	180.000	
7 Calcium (Ca) (Dissol	110.000	98.000	130.000	110.000	
8 Iron (Fe) (Dissolved	.110	.020	-.020	.090	
9 Magnesium (Mg) (Diss	39.000	38.000	41.000	39.000	
10 Potassium (K) (Disso	3.800	3.700	3.100	3.500	
11 Sodium (Na) (Dissolv	25.000	24.000	32.000	27.000	
12 Nitrogen (NPN)	2.700	2.100	18.000	5.000	
13 Nitrate					
14 Turbidity (NTU)	2.390	4.670	2.310	.480	
15 Ionic Str (PHREEQE)				.014	
16 Carbon (PHREEQE)				69.089	
17 Cat/Anion (PHREEQE)				1.027	
18 SI Calcite (PHREEQE)				-.291	
19 SI Gypsum (PHREEQE)				-1.264	
20 PCO2, atm (PHREEQE)				-1.398	
21 Silica (mg/L)	4.700	4.400	7.100	4.900	
22 D/H (ppt)				-73.000	
23 180/160 (ppt)				-10.400	

Coyote Spring

ANALYTE	1992/01/09	1992/07/22	1993/04/00	1993/07/00	1993/09/00
1 Alkalinity (field)	904.000	1886.000	943.000	823.000	911.000
2 Bromide	1.700	-.100	1.700	1.600	2.000
3 Chloride (Cl)	523.200	582.200	420.000	410.000	510.000

4 Fluoride (F) (Dissol	2.300	3.500	1.400	15.000	2.200
5 pH (field)	6.170	6.090	5.920	5.720	6.000
6 Sulfate (SO4)	144.900	138.500	92.000	10.000	100.000
7 Calcium (Ca) (Dissol	239.700	208.900	240.000	250.000	250.000
8 Iron (Fe) (Dissolved			.180	.220	.300
9 Magnesium (Mg) (Diss	53.500	50.200	50.000	52.000	.570
10 Potassium (K) (Disso	26.800	27.400	24.000	24.000	26.000
11 Sodium (Na) (Dissolv	308.400	316.800	330.000	340.000	370.000
12 Nitrogen (NPN)			1.300	1.200	.640
13 Nitrate	5.200	46.700			
14 Turbidity (NTU)					
15 Ionic Str (PHREEQE)					
16 Carbon (PHREEQE)					
17 Cat/Anion (PHREEQE)					
18 SI Calcite (PHREEQE)					
19 SI Gypsum (PHREEQE)					
20 PCO2, atm (PHREEQE)					
21 Silica (mg/L)					
22 D/H (ppt)					
23 18O/16O (ppt)					

Coyote Spring

ANALYTE	1993/12/00	1994/03/00	1994/06/00	1994/09/00	0000/00/00
1 Alkalinity (field)	956.000		893.000	202.000	
2 Bromide	2.000	2.100	2.100	2.000	
3 Chloride (Cl)	530.000	540.000	510.000	500.000	
4 Fluoride (F) (Dissol	2.300	1.700	1.700	1.700	
5 pH (field)	6.200	6.100	6.150	6.160	
6 Sulfate (SO4)	130.000	150.000	110.000	120.000	
7 Calcium (Ca) (Dissol	270.000	300.000	290.000	280.000	
8 Iron (Fe) (Dissolved	.900	.630	1.800	1.200	
9 Magnesium (Mg) (Diss	61.000	61.000	60.000	62.000	
10 Potassium (K) (Disso	28.000	28.000	28.000	29.000	
11 Sodium (Na) (Dissolv	200.000	380.000	360.000	400.000	
12 Nitrogen (NPN)	.400	.350	.370	.500	
13 Nitrate					
14 Turbidity (NTU)	8.000	11.500	18.800	17.500	
15 Ionic Str (PHREEQE)			.044		
16 Carbon (PHREEQE)			486.304		
17 Cat/Anion (PHREEQE)			1.038		
18 SI Calcite (PHREEQE)			-.049		
19 SI Gypsum (PHREEQE)			-1.320		
20 PCO2, atm (PHREEQE)			-.174		
21 Silica (mg/L)	8.400	8.100	8.400	8.200	
22 D/H (ppt)				-87.000	
23 18O/16O (ppt)				-11.600	

CWL-BW2

ANALYTE	1992/01/15	1992/07/29	1993/04/00	1993/07/00	1993/09/00
1 Alkalinity (field)		368.500	363.000	352.000	411.000
2 Bromide		1.000	.200	.670	.660
3 Chloride (Cl)		118.600	17.000	130.000	120.000
4 Fluoride (F) (Dissol		2.200	.500	1.700	1.900
5 pH (field)		7.100	7.140	6.800	6.820
6 Sulfate (SO4)		81.200	60.000	56.000	72.000
7 Calcium (Ca) (Dissol		88.700	120.000	140.000	126.000
8 Iron (Fe) (Dissolved			4.400	5.300	.370
9 Magnesium (Mg) (Diss		26.700	29.000	32.000	28.000
10 Potassium (K) (Disso		7.300	6.300	6.500	6.300
11 Sodium (Na) (Dissolv		71.600	85.000	82.000	85.000

12	Nitrogen (NPN)			6.400	5.400	1.500
13	Nitrate		6.100			
14	Turbidity (NTU)					
15	Ionic Str (PHREEQE)					
16	Carbon (PHREEQE)					
17	Cat/Anion (PHREEQE)					
18	SI Calcite (PHREEQE)					
19	SI Gypsum (PHREEQE)					
20	PCO2, atm (PHREEQE)					
21	Silica (mg/L)					
22	D/H (ppt)					
23	180/160 (ppt)					

CWL-BW2

	ANALYTE	1993/12/00	1994/03/00	1994/06/00	1994/09/00	0000/00/00
1	Alkalinity (field)	301.000	323.000	250.000	373.000	
2	Bromide	.660	.640	.680	.640	
3	Chloride (Cl)	130.000	130.000	130.000	130.000	
4	Fluoride (F) (Dissol	1.800	1.700	1.900	1.700	
5	pH (field)	6.890	6.730	6.970	6.850	
6	Sulfate (SO4)	78.000	76.000	82.000	77.000	
7	Calcium (Ca) (Dissol	120.000	130.000	110.000	130.000	
8	Iron (Fe) (Dissolved	4.600	3.300	1.500	5.500	
9	Magnesium (Mg) (Diss	29.000	32.000	29.000	30.000	
10	Potassium (K) (Disso	6.600	6.500	6.400	6.500	
11	Sodium (Na) (Dissolv	84.000	85.000	86.000	87.000	
12	Nitrogen (NPN)	1.500	1.600	1.600	1.500	
13	Nitrate					
14	Turbidity (NTU)	28.600	36.600	10.600	37.800	
15	Ionic Str (PHREEQE)				.017	
16	Carbon (PHREEQE)				113.778	
17	Cat/Anion (PHREEQE)				1.015	
18	SI Calcite (PHREEQE)				.059	
19	SI Gypsum (PHREEQE)				-1.576	
20	PCO2, atm (PHREEQE)				-1.224	
21	Silica (mg/L)		17.000	170.000	15.000	
22	D/H (ppt)				-74.000	
23	180/160 (ppt)				-10.200	

EOD Hill Well

	ANALYTE	1992/01/17	1992/07/31	1993/04/00	1993/07/00	1993/09/00
1	Alkalinity (field)	2180.500	1856.000	1925.000	1598.000	1790.000
2	Bromide	-.100	-.100	1.600	1.400	1.400
3	Chloride (Cl)	422.700	434.100	410.000	420.000	400.000
4	Fluoride (F) (Dissol	.500	7.000	1.600	1.500	2.500
5	pH (field)	6.420	6.490	6.050	6.180	6.150
6	Sulfate (SO4)	102.500	114.800	110.000	110.000	120.000
7	Calcium (Ca) (Dissol	434.400	124.000	550.000	570.000	530.000
8	Iron (Fe) (Dissolved			20.000	18.000	17.000
9	Magnesium (Mg) (Diss	95.100	97.300	101.000	110.000	105.000
10	Potassium (K) (Disso	28.600	40.600	37.000	40.000	39.000
11	Sodium (Na) (Dissolv	374.200	357.700	410.000	440.000	420.000
12	Nitrogen (NPN)			-.050	-.050	-.050
13	Nitrate	-.050	-.050			
14	Turbidity (NTU)					
15	Ionic Str (PHREEQE)					
16	Carbon (PHREEQE)					
17	Cat/Anion (PHREEQE)					
18	SI Calcite (PHREEQE)					
19	SI Gypsum (PHREEQE)					

20	PCO2, atm (PHREEQE)
21	Silica (mg/L)
22	D/H (ppt)
23	18O/16O (ppt)

EOD Hill Well

	ANALYTE	1993/12/00	1994/03/00	1994/06/00	1994/09/00	0000/00/00
1	Alkalinity (field)	1917.000	1997.000	1869.000	2118.000	
2	Bromide	1.500	1.800	2.200	1.500	
3	Chloride (Cl)	420.000	390.000	390.000	360.000	
4	Fluoride (F) (Dissol	1.800	1.700	1.600	1.600	
5	pH (field)	6.090	6.070	6.170	6.110	
6	Sulfate (SO4)	120.000	140.000	95.000	110.000	
7	Calcium (Ca) (Dissol	550.000	540.000	520.000	550.000	
8	Iron (Fe) (Dissolved	18.000	17.000	17.000	19.000	
9	Magnesium (Mg) (Diss	110.000	100.000	100.000	110.000	
10	Potassium (K) (Disso	39.000	38.000	39.000	39.000	
11	Sodium (Na) (Dissolv	420.000	410.000	420.000	410.000	
12	Nitrogen (NPN)	-.050	-.050	-.050	-.050	
13	Nitrate					
14	Turbidity (NTU)	4.500	5.230	5.230	3.540	
15	Ionic Str (PHREEQE)		.067			
16	Carbon (PHREEQE)		1175.200			
17	Cat/Anion (PHREEQE)		1.003			
18	SI Calcite (PHREEQE)		.392			
19	SI Gypsum (PHREEQE)		-1.121			
20	PCO2, atm (PHREEQE)		.237			
21	Silica (mg/L)	23.000	22.000	24.000	24.000	
22	D/H (ppt)				-100.000	
23	18O/16O (ppt)				-13.800	

Golf Course South Well

	ANALYTE	1992/01/22	1992/07/31	1993/04/00	1993/07/00	1993/09/00
1	Alkalinity (field)	141.000	118.000	132.000		117.000
2	Bromide	-.100		.610	.600	.600
3	Chloride (Cl)	32.900	42.600	44.000	45.000	44.000
4	Fluoride (F) (Dissol	.500	.400	.600	.400	.400
5	pH (field)	8.220	7.490	7.700	7.430	7.370
6	Sulfate (SO4)	53.000	72.900	59.000	60.000	55.000
7	Calcium (Ca) (Dissol	14.500	71.300	87.000	83.000	89.000
8	Iron (Fe) (Dissolved			-.020	-.020	-.020
9	Magnesium (Mg) (Diss	15.100	18.200	15.000	16.000	16.000
10	Potassium (K) (Disso	1.200	2.800	22.000	2.400	2.600
11	Sodium (Na) (Dissolv	20.200	23.100	20.000	20.000	22.000
12	Nitrogen (NPN)			21.000	20.000	19.000
13	Nitrate	96.400	-.050			
14	Turbidity (NTU)					
15	Ionic Str (PHREEQE)					
16	Carbon (PHREEQE)					
17	Cat/Anion (PHREEQE)					
18	SI Calcite (PHREEQE)					
19	SI Gypsum (PHREEQE)					
20	PCO2, atm (PHREEQE)					
21	Silica (mg/L)					
22	D/H (ppt)					
23	18O/16O (ppt)					

Golf Course South Well

	ANALYTE	1993/12/00	1994/03/00	1994/06/00	1994/09/00	0000/00/00
1	Alkalinity (field)	96.000	123.000		144.000	

2	Bromide	.590	.600	.610	.780
3	Chloride (Cl)	43.000	48.000	47.000	43.000
4	Fluoride (F) (Dissol	.400	.400	.500	.300
5	pH (field)	7.430	7.320	7.410	7.320
6	Sulfate (SO4)	62.000	65.000	68.000	60.000
7	Calcium (Ca) (Dissol	88.000	86.000	85.000	91.000
8	Iron (Fe) (Dissolved	-.020	-.020	.020	-.020
9	Magnesium (Mg) (Diss	17.000	17.000	17.000	17.000
10	Potassium (K) (Disso	2.400	2.400	2.600	2.300
11	Sodium (Na) (Dissolv	21.000	21.000	22.000	21.000
12	Nitrogen (NPN)	20.000	19.000	20.000	20.000
13	Nitrate				
14	Turbidity (NTU)	.120	.250	.160	.840
15	Ionic Str (PHREEQE)		.009		
16	Carbon (PHREEQE)		32.219		
17	Cat/Anion (PHREEQE)		1.309		
18	SI Calcite (PHREEQE)		-.057		
19	SI Gypsum (PHREEQE)		-1.694		
20	PCO2, atm (PHREEQE)		-2.163		
21	Silica (mg/L)	13.000	13.000	13.000	12.000
22	D/H (ppt)				-74.000
23	18O/16O (ppt)				-10.300

Greystone Manor Well

	ANALYTE	1992/01/16	1992/07/30	1993/04/00	1993/07/00	1993/09/00
1	Alkalinity (field)	342.000	312.500	280.000		358.000
2	Bromide	-.100	.500	.460	.440	.480
3	Chloride (Cl)	79.000	143.100	80.000	83.000	88.000
4	Fluoride (F) (Dissol	2.000	1.300	.700	.700	.700
5	pH (field)	7.480	7.580	7.350	5.970	7.220
6	Sulfate (SO4)	39.200	79.500	38.000	47.000	45.000
7	Calcium (Ca) (Dissol	101.300	62.200	99.000	120.000	106.000
8	Iron (Fe) (Dissolved			18.000	41.000	21.000
9	Magnesium (Mg) (Diss	25.200	22.900	23.000	25.000	24.000
10	Potassium (K) (Disso	3.200	5.100	5.900	6.100	6.500
11	Sodium (Na) (Dissolv	61.300	59.500	64.000	65.000	69.000
12	Nitrogen (NPN)			5.500	5.000	4.800
13	Nitrate	21.800	35.200			
14	Turbidity (NTU)					
15	Ionic Str (PHREEQE)					
16	Carbon (PHREEQE)					
17	Cat/Anion (PHREEQE)					
18	SI Calcite (PHREEQE)					
19	SI Gypsum (PHREEQE)					
20	PCO2, atm (PHREEQE)					
21	Silica (mg/L)					
22	D/H (ppt)					
23	18O/16O (ppt)					

Greystone Manor Well

	ANALYTE	1993/12/00	1994/03/00	1994/06/00	1994/09/00	0000/00/00
1	Alkalinity (field)	279.000	256.000	309.000	340.000	
2	Bromide	.500	.440	.480	.580	
3	Chloride (Cl)	84.000	78.000	82.000	92.000	
4	Fluoride (F) (Dissol	.700	.620	.700	.600	
5	pH (field)	7.180	7.110	7.350	6.940	
6	Sulfate (SO4)	44.000	-2.000	50.000	45.000	
7	Calcium (Ca) (Dissol	110.000	100.000	110.000	110.000	
8	Iron (Fe) (Dissolved	3.500	1.900	11.000	22.000	
9	Magnesium (Mg) (Diss	25.000	24.000	26.000	27.000	

10 Potassium (K) (Disso	4.600	4.600	6.000	6.000
11 Sodium (Na) (Dissolv	64.000	64.000	65.000	69.000
12 Nitrogen (NPN)	5.000	3.800	4.900	4.500
13 Nitrate				
14 Turbidity (NTU)	137.000	129.000	93.600	191.000
15 Ionic Str (PHREEQE)				.014
16 Carbon (PHREEQE)				99.724
17 Cat/Anion (PHREEQE)				1.054
18 SI Calcite (PHREEQE)				.064
19 SI Gypsum (PHREEQE)				-1.837
20 PCO2, atm (PHREEQE)				-1.350
21 Silica (mg/L)	13.000	7.700	10.000	11.000
22 D/H (ppt)				-73.000
23 18O/16O (ppt)				-10.300

Hubbell Spring

ANALYTE	1992/01/10	1992/07/22	1993/04/00	1993/07/00	1993/09/00
1 Alkalinity (field)	189.000	169.500	192.000	238.000	178.000
2 Bromide	.300	.300	.360	.350	.400
3 Chloride (Cl)	29.900	31.900	35.000	34.000	34.000
4 Fluoride (F) (Dissol	1.100	.500	.900	.900	1.000
5 pH (field)	7.400	7.380	6.690	6.200	7.710
6 Sulfate (SO4)	281.500	278.800	220.000	180.000	190.000
7 Calcium (Ca) (Dissol	78.200	79.200	74.000	82.000	77.000
8 Iron (Fe) (Dissolved			-.020	-.020	-.020
9 Magnesium (Mg) (Diss	30.100	32.800	32.000	32.000	32.000
10 Potassium (K) (Disso	1.100	1.900	1.400	1.600	1.400
11 Sodium (Na) (Dissolv	53.400	56.400	54.000	57.000	56.000
12 Nitrogen (NPN)			.750	.740	.690
13 Nitrate	3.100	2.700			
14 Turbidity (NTU)					
15 Ionic Str (PHREEQE)				.013	
16 Carbon (PHREEQE)				128.254	
17 Cat/Anion (PHREEQE)				.975	
18 SI Calcite (PHREEQE)				-.978	
19 SI Gypsum (PHREEQE)				-1.362	
20 PCO2, atm (PHREEQE)				-.760	
21 Silica (mg/L)					
22 D/H (ppt)					
23 18O/16O (ppt)					

Hubbell Spring

ANALYTE	1993/12/00	1994/03/00	1994/06/00	1994/09/00	0000/00/00
1 Alkalinity (field)	165.000	143.000	190.000	1042.000	
2 Bromide	.300	.340	.320	.480	
3 Chloride (Cl)	32.000	21.000	32.000	30.000	
4 Fluoride (F) (Dissol	.900	.900	1.000	.800	
5 pH (field)	7.630	7.510	7.970	7.320	
6 Sulfate (SO4)	220.000	210.000	180.000	210.000	
7 Calcium (Ca) (Dissol	85.000	80.000	82.000	80.000	
8 Iron (Fe) (Dissolved	-.020	-.020	-.020	.030	
9 Magnesium (Mg) (Diss	33.000	31.000	31.000	32.000	
10 Potassium (K) (Disso	1.200	1.200	1.400	1.300	
11 Sodium (Na) (Dissolv	57.000	53.000	53.000	56.000	
12 Nitrogen (NPN)	.700	.640	.790	.900	
13 Nitrate					
14 Turbidity (NTU)	.610	3.060	1.310	.730	
15 Ionic Str (PHREEQE)					
16 Carbon (PHREEQE)					
17 Cat/Anion (PHREEQE)					

18 SI Calcite (PHREEQE)					
19 SI Gypsum (PHREEQE)					
20 PCO2, atm (PHREEQE)					
21 Silica (mg/L)	14.000	14.000	14.000	14.000	
22 D/H (ppt)				-76.000	
23 180/160 (ppt)				-10.100	

KAFB-10 Well

ANALYTE	1992/01/13	1992/07/27	1993/04/00	1993/07/00	1993/09/00
1 Alkalinity (field)	14.000	40.000			217.000
2 Bromide	.400	.300	.310		.300
3 Chloride (Cl)	330.000	203.500	81.000		120.000
4 Fluoride (F) (Dissol	2.900	1.300	1.200		1.300
5 pH (field)	8.620	8.580	8.190		7.900
6 Sulfate (SO4)	22.200	51.900	44.000		46.000
7 Calcium (Ca) (Dissol	59.000	29.900	29.000		38.000
8 Iron (Fe) (Dissolved			3.300		3.300
9 Magnesium (Mg) (Diss	6.400	8.800	9.300		12.000
10 Potassium (K) (Disso	12.300	8.700	6.000		6.800
11 Sodium (Na) (Dissolv	84.500	68.600	65.000		77.000
12 Nitrogen (NPN)			.400		2.300
13 Nitrate	-.050	-.050			
14 Turbidity (NTU)					
15 Ionic Str (PHREEQE)					
16 Carbon (PHREEQE)					
17 Cat/Anion (PHREEQE)					
18 SI Calcite (PHREEQE)					
19 SI Gypsum (PHREEQE)					
20 PCO2, atm (PHREEQE)					
21 Silica (mg/L)					
22 D/H (ppt)					
23 180/160 (ppt)					

KAFB-10 Well

ANALYTE	1993/12/00	1994/03/00	1994/06/00	1994/09/00	0000/00/00
1 Alkalinity (field)	65.000		391.000		
2 Bromide	.300	.280	.330		
3 Chloride (Cl)	130.000	70.000	98.000		
4 Fluoride (F) (Dissol	1.300	1.300	1.600		
5 pH (field)	7.580	7.380	7.680		
6 Sulfate (SO4)	48.000	58.000	45.000		
7 Calcium (Ca) (Dissol	27.000	47.000	37.000		
8 Iron (Fe) (Dissolved	1.600	16.000	4.700		
9 Magnesium (Mg) (Diss	11.000	15.000	12.000		
10 Potassium (K) (Disso	6.000	6.200	4.500		
11 Sodium (Na) (Dissolv	70.000	62.000	57.000		
12 Nitrogen (NPN)	.800	2.800	3.400		
13 Nitrate					
14 Turbidity (NTU)	30.200	108.000	30.500		
15 Ionic Str (PHREEQE)	.007				
16 Carbon (PHREEQE)	16.357				
17 Cat/Anion (PHREEQE)	.912				
18 SI Calcite (PHREEQE)	-.551				
19 SI Gypsum (PHREEQE)	-2.244				
20 PCO2, atm (PHREEQE)	-2.693				
21 Silica (mg/L)	1.500	9.100	5.000		
22 D/H (ppt)					
23 180/160 (ppt)					

LF/DM-1 Well

ANALYTE	1992/01/24	1992/08/06	1993/04/00	1993/07/00	1993/09/00
1 Alkalinity (field)	105.500	79.000		40.000	103.000
2 Bromide	-.100	-.100		-.100	-.100
3 Chloride (Cl)	18.100	4.200		6.300	6.600
4 Fluoride (F) (Dissol	1.300	0.300		.500	.500
5 pH (field)	8.020	8.000		7.980	7.760
6 Sulfate (SO4)	22.300	21.300		27.000	26.000
7 Calcium (Ca) (Dissol	25.700	29.100		32.000	32.000
8 Iron (Fe) (Dissolved				.040	-.020
9 Magnesium (Mg) (Diss	4.300	5.000		5.100	4.900
10 Potassium (K) (Disso	1.000	2.200		2.300	2.000
11 Sodium (Na) (Dissolv	17.100	18.400		19.000	18.000
12 Nitrogen (NPN)				.450	-.050
13 Nitrate	-.050	-.050			
14 Turbidity (NTU)					
15 Ionic Str (PHREEQE)					
16 Carbon (PHREEQE)					
17 Cat/Anion (PHREEQE)					
18 SI Calcite (PHREEQE)					
19 SI Gypsum (PHREEQE)					
20 PCO2, atm (PHREEQE)					
21 Silica (mg/L)					
22 D/H (ppt)					
23 18O/16O (ppt)					

LF/DM-1 Well

ANALYTE	1993/12/00	1994/03/00	1994/06/00	1994/09/00	0000/00/00
1 Alkalinity (field)	98.000	127.000	102.000	112.000	
2 Bromide	-.050	-.050	-.050	-.100	
3 Chloride (Cl)	6.000	5.800	5.600	6.600	
4 Fluoride (F) (Dissol	.500	0.500	.500	.500	
5 pH (field)	7.930	7.670	7.800	7.840	
6 Sulfate (SO4)	27.000	28.000	25.000	26.000	
7 Calcium (Ca) (Dissol	30.000	30.000	32.000	30.000	
8 Iron (Fe) (Dissolved	.030	.040	.020	-.020	
9 Magnesium (Mg) (Diss	4.700	4.900	5.000	4.800	
10 Potassium (K) (Disso	2.100	2.100	2.300	2.000	
11 Sodium (Na) (Dissolv	18.000	19.000	20.000	18.000	
12 Nitrogen (NPN)	-.050	.050	-.050	.070	
13 Nitrate					
14 Turbidity (NTU)	.500	.600	.610	.490	
15 Ionic Str (PHREEQE)	.004				
16 Carbon (PHREEQE)	23.868				
17 Cat/Anion (PHREEQE)	1.012				
18 SI Calcite (PHREEQE)	.067				
19 SI Gypsum (PHREEQE)	-2.370				
20 PCO2, atm (PHREEQE)	-2.859				
21 Silica (mg/L)	17.000	17.000	16.000	16.000	
22 D/H (ppt)				-100.000	
23 18O/16O (ppt)				-13.700	

LF/DM-2 Well

ANALYTE	1992/01/23	1992/08/04	1993/04/00	1993/07/00	1993/09/00
1 Alkalinity (field)	177.000	140.500	157.000	782.000	138.000
2 Bromide	-.100	-.100	.210	.180	.180
3 Chloride (Cl)	15.300	15.500	15.000	16.000	16.000
4 Fluoride (F) (Dissol	-.100	.300	.300	.400	.400
5 pH (field)	8.200	7.530	7.700	7.320	7.430
6 Sulfate (SO4)	76.300	96.100	74.000	79.000	66.000
7 Calcium (Ca) (Dissol	61.300	55.800	271.000	71.000	70.000

8	Iron (Fe) (Dissolved			.030	.020	-.020
9	Magnesium (Mg) (Diss	12.000	13.100	13.000	13.000	13.000
10	Potassium (K) (Disso	1.300	2.600	2.300	2.300	2.500
11	Sodium (Na) (Dissolv	22.200	23.500	24.000	24.000	24.000
12	Nitrogen (NPN)			4.000	4.300	4.100
13	Nitrate	18.700	19.200			
14	Turbidity (NTU)					
15	Ionic Str (PHREEQE)					
16	Carbon (PHREEQE)					
17	Cat/Anion (PHREEQE)					
18	SI Calcite (PHREEQE)					
19	SI Gypsum (PHREEQE)					
20	PCO2, atm (PHREEQE)					
21	Silica (mg/L)					
22	D/H (ppt)					
23	18O/16O (ppt)					

LF/DM-2 Well

	ANALYTE	1993/12/00	1994/03/00	1994/06/00	1994/09/00	0000/00/00
1	Alkalinity (field)	146.000	167.000	136.000	175.000	
2	Bromide	.200	.190	.190	.190	
3	Chloride (Cl)	16.000	17.000	15.000	17.000	
4	Fluoride (F) (Dissol	.320	.400	.400	.300	
5	pH (field)	7.320	7.340	7.410	7.350	
6	Sulfate (SO4)	78.000	80.000	69.000	77.000	
7	Calcium (Ca) (Dissol	66.000	73.000	73.000	72.000	
8	Iron (Fe) (Dissolved	.120	.060	.150	.070	
9	Magnesium (Mg) (Diss	12.000	13.000	14.000	13.000	
10	Potassium (K) (Disso	2.100	2.400	2.600	2.300	
11	Sodium (Na) (Dissolv	22.000	24.000	26.000	24.000	
12	Nitrogen (NPN)	4.000	2.000	4.000	4.200	
13	Nitrate					
14	Turbidity (NTU)	4.300	1.350	6.470	3.050	
15	Ionic Str (PHREEQE)				.008	
16	Carbon (PHREEQE)				45.603	
17	Cat/Anion (PHREEQE)				1.035	
18	SI Calcite (PHREEQE)				.048	
19	SI Gypsum (PHREEQE)				-1.680	
20	PCO2, atm (PHREEQE)				-2.037	
21	Silica (mg/L)	14.000	14.000	14.000	13.000	
22	D/H (ppt)				-74.000	
23	18O/16O (ppt)				-10.600	

MVMW-J Well

	ANALYTE	1992/01/21	1992/08/07	1993/04/00	1993/07/00	1993/09/00
1	Alkalinity (field)	94.500	96.500	145.000	85.000	140.000
2	Bromide	-.100	-.100	.120	-.100	.100
3	Chloride (Cl)	11.000	6.800	9.100	8.300	7.500
4	Fluoride (F) (Dissol	-.100	.300	.400	.400	.300
5	pH (field)	7.950	7.780	7.300	6.780	7.740
6	Sulfate (SO4)	23.300	27.400	25.000	24.000	30.000
7	Calcium (Ca) (Dissol	29.900	33.000	44.000	52.000	54.000
8	Iron (Fe) (Dissolved			2.700	2.200	3.500
9	Magnesium (Mg) (Diss	3.600	4.300	5.900	6.000	6.300
10	Potassium (K) (Disso	1.000	2.200	2.800	3.100	3.000
11	Sodium (Na) (Dissolv	16.600	17.500	20.000	20.000	20.000
12	Nitrogen (NPN)			.560	13.000	14.000
13	Nitrate	9.300	31.200			
14	Turbidity (NTU)					
15	Ionic Str (PHREEQE)					

16 Carbon (PHREEQE)
17 Cat/Anion (PHREEQE)
18 SI Calcite (PHREEQE)
19 SI Gypsum (PHREEQE)
20 PCO2, atm (PHREEQE)
21 Silica (mg/L)
22 D/H (ppt)
23 18O/16O (ppt)

MVMW-J Well

ANALYTE	1993/12/00	1994/03/00	1994/06/00	1994/09/00	0000/00/00
1 Alkalinity (field)	97.000	168.000	127.000	109.000	
2 Bromide	.100	.100	.240	.120	
3 Chloride (Cl)	8.900	8.500	8.400	9.500	
4 Fluoride (F) (Dissol	.400	.400	.400	.400	
5 pH (field)	7.860	7.760	7.840	7.710	
6 Sulfate (SO4)	27.000	25.000	30.000	23.000	
7 Calcium (Ca) (Dissol	47.000	51.000	68.000	65.000	
8 Iron (Fe) (Dissolved	1.300	2.900	8.800	8.900	
9 Magnesium (Mg) (Diss	5.500	6.000	7.700	7.900	
10 Potassium (K) (Disso	5.800	3.900	4.900	5.200	
11 Sodium (Na) (Dissolv	27.000	23.000	22.000	25.000	
12 Nitrogen (NPN)	13.000	11.000	12.000	14.000	
13 Nitrate					
14 Turbidity (NTU)	28.400	59.000	386.000	350.000	
15 Ionic Str (PHREEQE)		.006			
16 Carbon (PHREEQE)		41.431			
17 Cat/Anion (PHREEQE)		1.005			
18 SI Calcite (PHREEQE)		.331			
19 SI Gypsum (PHREEQE)		-2.239			
20 PCO2, atm (PHREEQE)		-2.461			
21 Silica (mg/L)	24.000	25.000	39.000	32.000	
22 D/H (ppt)				-97.000	
23 18O/16O (ppt)				-13.500	

MVMW-K Well

ANALYTE	1992/01/21	1992/08/07	1993/04/00	1993/07/00	1993/09/00
1 Alkalinity (field)	105.000	85.500	169.000	93.000	134.000
2 Bromide	-.100	-.100	.160	.150	-.100
3 Chloride (Cl)	361.900	7.400	12.000	11.000	9.200
4 Fluoride (F) (Dissol	4.900	.300	.400	.500	.400
5 pH (field)	7.670	7.820	8.080	7.030	7.880
6 Sulfate (SO4)	29.100	32.700	29.000	33.000	31.000
7 Calcium (Ca) (Dissol	47.300	37.600	53.000	57.000	54.000
8 Iron (Fe) (Dissolved			1.700	1.500	3.500
9 Magnesium (Mg) (Diss	5.100	4.700	5.900	6.000	5.800
10 Potassium (K) (Disso	1.000	2.200	2.500	2.600	3.900
11 Sodium (Na) (Dissolv	22.200	21.000	23.000	23.000	25.000
12 Nitrogen (NPN)			1.400	20.000	11.000
13 Nitrate	-.050	34.400			
14 Turbidity (NTU)					
15 Ionic Str (PHREEQE)			.006		
16 Carbon (PHREEQE)			40.617		
17 Cat/Anion (PHREEQE)			.970		
18 SI Calcite (PHREEQE)			.657		
19 SI Gypsum (PHREEQE)			-2.167		
20 PCO2, atm (PHREEQE)			-2.786		
21 Silica (mg/L)					
22 D/H (ppt)					
23 18O/16O (ppt)					

MVMW-K Well

	ANALYTE	1993/12/00	1994/03/00	1994/06/00	1994/09/00	0000/00/00
1	Alkalinity (field)	92.000		98.000	126.000	
2	Bromide	.100	.080	.110	-.100	
3	Chloride (Cl)	10.000	8.900	8.600	10.000	
4	Fluoride (F) (Dissol	.400	.400	.500	.400	
5	pH (field)	7.760	7.600	7.930	7.900	
6	Sulfate (SO4)	30.000	35.000	40.000	38.000	
7	Calcium (Ca) (Dissol	59.000	65.000	50.000	65.000	
8	Iron (Fe) (Dissolved	2.400	11.000	5.900	14.000	
9	Magnesium (Mg) (Diss	6.500	7.000	6.400	7.600	
10	Potassium (K) (Disso	5.000	4.900	5.000	5.400	
11	Sodium (Na) (Dissolv	29.000	23.000	26.000	26.000	
12	Nitrogen (NPN)	20.000	7.800	14.000	31.000	
13	Nitrate					
14	Turbidity (NTU)	63.200	434.000	720.000	357.000	
15	Ionic Str (PHREEQE)					
16	Carbon (PHREEQE)					
17	Cat/Anion (PHREEQE)					
18	SI Calcite (PHREEQE)					
19	SI Gypsum (PHREEQE)					
20	PCO2, atm (PHREEQE)					
21	Silica (mg/L)	19.000	33.000	29.000	36.000	
22	D/H (ppt)				-99.000	
23	18O/16O (ppt)				-13.500	

MWL-BW1

	ANALYTE	1992/01/15	1992/07/29	1993/04/00	1993/07/00	1993/09/00
1	Alkalinity (field)	237.000	236.500	256.000	215.000	
2	Bromide	-.100	-.100	.230	.260	
3	Chloride (Cl)	28.100	33.000	29.000	29.000	
4	Fluoride (F) (Dissol	.800	.900	.900	.900	
5	pH (field)	7.500	7.440	7.550	7.590	
6	Sulfate (SO4)	58.900	55.900	46.000	47.000	
7	Calcium (Ca) (Dissol	58.600	39.000	46.600	57.000	
8	Iron (Fe) (Dissolved			.055	24.000	
9	Magnesium (Mg) (Diss	18.900	16.200	17.900	20.000	
10	Potassium (K) (Disso	3.200	4.000	2.700	3.200	
11	Sodium (Na) (Dissolv	49.100	50.200	46.900	51.000	
12	Nitrogen (NPN)			5.700	1.600	
13	Nitrate	27.200	28.000			
14	Turbidity (NTU)					
15	Ionic Str (PHREEQE)					
16	Carbon (PHREEQE)					
17	Cat/Anion (PHREEQE)					
18	SI Calcite (PHREEQE)					
19	SI Gypsum (PHREEQE)					
20	PCO2, atm (PHREEQE)					
21	Silica (mg/L)					
22	D/H (ppt)					
23	18O/16O (ppt)					

MWL-BW1

	ANALYTE	1993/12/00	1994/03/00	1994/06/00	1994/09/00	0000/00/00
1	Alkalinity (field)	173.000		203.000	234.000	
2	Bromide	.230	.260	.220	-.100	
3	Chloride (Cl)	28.000	29.000	29.000	25.600	
4	Fluoride (F) (Dissol	.900	.900	.900	.790	
5	pH (field)	7.460	7.700	7.770	7.530	

6 Sulfate (SO4)	45.000	52.000	49.000	42.500
7 Calcium (Ca) (Dissol	55.000	54.000	55.000	55.800
8 Iron (Fe) (Dissolved	.030	.110	.130	.057
9 Magnesium (Mg) (Diss	20.000	19.000	20.000	20.000
10 Potassium (K) (Disso	3.300	3.100	3.100	3.500
11 Sodium (Na) (Dissolv	52.000	50.000	52.000	56.900
12 Nitrogen (NPN)	5.600	5.400	5.500	5.600
13 Nitrate				
14 Turbidity (NTU)	.640	2.020	14.100	1.900
15 Ionic Str (PHREEQE)				.009
16 Carbon (PHREEQE)				59.177
17 Cat/Anion (PHREEQE)				1.117
18 SI Calcite (PHREEQE)				.243
19 SI Gypsum (PHREEQE)				-2.050
20 PCO2, atm (PHREEQE)				-2.093
21 Silica (mg/L)		14.000	14.000	
22 D/H (ppt)				
23 18O/16O (ppt)				

NW-TA3 Well

ANALYTE	1992/01/00	1992/07/28	1993/04/00	1993/07/00	1993/09/00
1 Alkalinity (field)	160.500	165.000	155.000		153.000
2 Bromide	-.100	-.100	.640	.210	.210
3 Chloride (Cl)	16.300	17.500	130.000	16.000	17.000
4 Fluoride (F) (Dissol	.300	.300	1.700	.400	.400
5 pH (field)	7.320	7.340	7.590	7.400	7.510
6 Sulfate (SO4)	86.200	81.300	73.000	56.000	75.000
7 Calcium (Ca) (Dissol	54.400	43.900	56.000	63.000	61.000
8 Iron (Fe) (Dissolved			-.020	.660	.090
9 Magnesium (Mg) (Diss	14.400	13.000	15.000	16.000	15.000
10 Potassium (K) (Disso	4.300	4.700	43.000	4.700	4.400
11 Sodium (Na) (Dissolv	21.100	20.900	22.000	22.000	22.000
12 Nitrogen (NPN)			1.500	6.400	6.200
13 Nitrate	26.900	30.000			
14 Turbidity (NTU)					
15 Ionic Str (PHREEQE)					.008
16 Carbon (PHREEQE)					38.815
17 Cat/Anion (PHREEQE)					1.052
18 SI Calcite (PHREEQE)					.084
19 SI Gypsum (PHREEQE)					-1.748
20 PCO2, atm (PHREEQE)					-2.254
21 Silica (mg/L)					
22 D/H (ppt)					
23 18O/16O (ppt)					

NW-TA3 Well

ANALYTE	1993/12/00	1994/03/00	1994/06/00	1994/09/00	0000/00/00
1 Alkalinity (field)	157.000	127.000	115.000	150.000	
2 Bromide	.240	.180	.200	.160	
3 Chloride (Cl)	17.000	16.000	16.000	15.000	
4 Fluoride (F) (Dissol	.400	.400	.400	.300	
5 pH (field)	7.460	7.290	7.590	7.310	
6 Sulfate (SO4)	60.000	57.000	64.000	61.000	
7 Calcium (Ca) (Dissol	60.000	65.000	56.000	65.000	
8 Iron (Fe) (Dissolved	-.020	.020	-.020	.020	
9 Magnesium (Mg) (Diss	15.000	16.000	15.000	16.000	
10 Potassium (K) (Disso	4.400	4.400	4.400	4.100	
11 Sodium (Na) (Dissolv	21.000	22.000	22.000	21.000	
12 Nitrogen (NPN)	6.300	6.100	6.500	6.400	
13 Nitrate					

14 Turbidity (NTU)	.220	.510	.750	.670	
15 Ionic Str (PHREEQE)					
16 Carbon (PHREEQE)					
17 Cat/Anion (PHREEQE)					
18 SI Calcite (PHREEQE)					
19 SI Gypsum (PHREEQE)					
20 PCO2, atm (PHREEQE)					
21 Silica (mg/L)		15.000	15.000	15.000	
22 D/H (ppt)				-71.000	
23 180/160 (ppt)				-10.300	

Schoolhouse Well

ANALYTE	1992/01/16	1992/07/30	1993/04/00	1993/07/00	1993/09/00
1 Alkalinity (field)	427.500	391.000	402.000	391.000	268.000
2 Bromide	.600	.700	.710	.680	.670
3 Chloride (Cl)	145.300	-2.000	150.000	150.000	140.000
4 Fluoride (F) (Dissol	1.500	1.800	1.400	1.400	1.400
5 pH (field)	7.000	6.960	6.820	6.720	6.940
6 Sulfate (SO4)	70.600	80.700	60.000	54.000	61.000
7 Calcium (Ca) (Dissol	150.100	112.300	140.000	160.000	137.000
8 Iron (Fe) (Dissolved			2.200	.320	23.000
9 Magnesium (Mg) (Diss	26.300	27.000	25.000	27.000	25.000
10 Potassium (K) (Disso	6.900	7.900	6.100	6.700	7.400
11 Sodium (Na) (Dissolv	158.100	81.200	92.000	95.000	92.000
12 Nitrogen (NPN)			3.900	4.600	3.300
13 Nitrate	20.700	25.600			
14 Turbidity (NTU)					
15 Ionic Str (PHREEQE)			.018		
16 Carbon (PHREEQE)			124.432		
17 Cat/Anion (PHREEQE)			.976		
18 SI Calcite (PHREEQE)			.093		
19 SI Gypsum (PHREEQE)			-1.656		
20 PCO2, atm (PHREEQE)			-1.163		
21 Silica (mg/L)					
22 D/H (ppt)					
23 180/160 (ppt)					

Schoolhouse Well

ANALYTE	1993/12/00	1994/03/00	1994/06/00	1994/09/00	0000/00/00
1 Alkalinity (field)	330.000	334.000	376.000	438.000	
2 Bromide	.720	.680	.700	.710	
3 Chloride (Cl)	150.000	-.500	130.000	160.000	
4 Fluoride (F) (Dissol	1.400	1.400	1.400	1.400	
5 pH (field)	6.760	6.670	6.870	6.600	
6 Sulfate (SO4)	62.000	63.000	61.000	62.000	
7 Calcium (Ca) (Dissol	140.000	150.000	150.000	150.000	
8 Iron (Fe) (Dissolved	1.600	1.300	1.300	1.100	
9 Magnesium (Mg) (Diss	25.000	27.000	26.000	26.000	
10 Potassium (K) (Disso	6.000	6.400	6.300	5.900	
11 Sodium (Na) (Dissolv	90.000	95.000	93.000	88.000	
12 Nitrogen (NPN)	3.500	3.800	4.200	4.400	
13 Nitrate					
14 Turbidity (NTU)	5.920	6.900	6.960	5.390	
15 Ionic Str (PHREEQE)					
16 Carbon (PHREEQE)					
17 Cat/Anion (PHREEQE)					
18 SI Calcite (PHREEQE)					
19 SI Gypsum (PHREEQE)					
20 PCO2, atm (PHREEQE)					
21 Silica (mg/L)	9.600	10.000	10.000	10.000	

22 D/H (ppt)				-73.000	
23 18O/16O (ppt)				-10.100	

Sol se Mete Spring

ANALYTE	1992/02/05	1992/07/22	1993/04/00	1993/07/00	1993/09/00
1 Alkalinity (field)		205.000	288.000	216.000	225.000
2 Bromide	.400	.300	.400	.420	.400
3 Chloride (Cl)	25.900	27.200	25.000	27.000	27.000
4 Fluoride (F) (Dissol	.200	.500	.400	.400	.500
5 pH (field)		6.800	5.480		7.340
6 Sulfate (SO4)	93.200	97.800	68.000	60.000	65.000
7 Calcium (Ca) (Dissol	54.400	85.400	96.000	110.000	100.000
8 Iron (Fe) (Dissolved			-.020	.040	-.020
9 Magnesium (Mg) (Diss	13.200	15.600	17.000	17.000	17.000
10 Potassium (K) (Disso	1.700	1.700	1.600	1.700	1.600
11 Sodium (Na) (Dissolv	11.100	11.700	11.000	11.000	11.000
12 Nitrogen (NPN)			1.200	1.300	1.200
13 Nitrate	5.400	5.500			
14 Turbidity (NTU)					
15 Ionic Str (PHREEQE)					.010
16 Carbon (PHREEQE)					58.656
17 Cat/Anion (PHREEQE)					1.048
18 SI Calcite (PHREEQE)					.274
19 SI Gypsum (PHREEQE)					-1.656
20 PCO2, atm (PHREEQE)					-1.923
21 Silica (mg/L)					
22 D/H (ppt)					
23 18O/16O (ppt)					

Sol se Mete Spring

ANALYTE	1993/12/00	1994/03/00	1994/06/00	1994/09/00	0000/00/00
1 Alkalinity (field)			205.000	230.000	
2 Bromide	.400	.380	.400	.370	
3 Chloride (Cl)	26.000	26.000	24.000	24.000	
4 Fluoride (F) (Dissol	.400	.400	.400	.300	
5 pH (field)	7.500	7.360	7.530	7.090	
6 Sulfate (SO4)	78.000	84.000	70.000	81.000	
7 Calcium (Ca) (Dissol	100.000	120.000	110.000	110.000	
8 Iron (Fe) (Dissolved	-.020	-.020	-.020	-.020	
9 Magnesium (Mg) (Diss	17.000	17.000	18.000	17.000	
10 Potassium (K) (Disso	1.600	1.400	1.600	1.500	
11 Sodium (Na) (Dissolv	11.000	11.000	12.000	12.000	
12 Nitrogen (NPN)	1.200	1.200	1.300	1.100	
13 Nitrate					
14 Turbidity (NTU)	1.050	1.410	.700	.610	
15 Ionic Str (PHREEQE)					
16 Carbon (PHREEQE)					
17 Cat/Anion (PHREEQE)					
18 SI Calcite (PHREEQE)					
19 SI Gypsum (PHREEQE)					
20 PCO2, atm (PHREEQE)					
21 Silica (mg/L)	8.800	8.900	9.800	8.600	
22 D/H (ppt)				-78.000	
23 18O/16O (ppt)				-10.700	

South Fence Well #1

ANALYTE	1992/01/00	1992/07/00	1993/04/00	1993/07/00	1993/09/00
1 Alkalinity (field)			407.000		507.000
2 Bromide			.670	.630	.650
3 Chloride (Cl)			130.000	130.000	130.000

4 Fluoride (F) (Dissol			1.700	1.700	1.700
5 pH (field)			6.810	6.600	6.680
6 Sulfate (SO4)			67.000	70.000	71.000
7 Calcium (Ca) (Dissol			148.000	160.000	150.000
8 Iron (Fe) (Dissolved			.780	-.020	-.020
9 Magnesium (Mg) (Diss			35.000	37.000	35.000
10 Potassium (K) (Disso			7.200	7.300	7.200
11 Sodium (Na) (Dissolv			78.000	80.000	77.000
12 Nitrogen (NPN)			.950	.900	.960
13 Nitrate					
14 Turbidity (NTU)					
15 Ionic Str (PHREEQE)					
16 Carbon (PHREEQE)					
17 Cat/Anion (PHREEQE)					
18 SI Calcite (PHREEQE)					
19 SI Gypsum (PHREEQE)					
20 PCO2, atm (PHREEQE)					
21 Silica (mg/L)					
22 D/H (ppt)					
23 18O/16O (ppt)					

South Fence Well #1

ANALYTE	1993/12/00	1994/03/00	1994/06/00	1994/09/00	0000/00/00
1 Alkalinity (field)	325.000	395.000	380.000	446.000	
2 Bromide	.650	.650	.640	.690	
3 Chloride (Cl)	140.000	130.000	130.000	130.000	
4 Fluoride (F) (Dissol	1.900	1.700	1.700	1.600	
5 pH (field)	6.690	6.700	6.820	6.730	
6 Sulfate (SO4)	70.000	71.000	65.000	68.000	
7 Calcium (Ca) (Dissol	150.000	150.000	150.000	150.000	
8 Iron (Fe) (Dissolved	-.020	-.020	.030	.070	
9 Magnesium (Mg) (Diss	35.000	35.000	35.000	37.000	
10 Potassium (K) (Disso	7.100	6.900	6.600	7.100	
11 Sodium (Na) (Dissolv	77.000	77.000	74.000	78.000	
12 Nitrogen (NPN)	.870	.870	.890	.930	
13 Nitrate					
14 Turbidity (NTU)	.180	.260	.980	1.000	
15 Ionic Str (PHREEQE)				.019	
16 Carbon (PHREEQE)				145.081	
17 Cat/Anion (PHREEQE)				1.008	
18 SI Calcite (PHREEQE)				.067	
19 SI Gypsum (PHREEQE)				-1.598	
20 PCO2, atm (PHREEQE)				-1.029	
21 Silica (mg/L)	1.600	16.000	16.000	16.000	
22 D/H (ppt)				-73.000	
23 18O/16O (ppt)				-10.300	

South Fence Well #2

ANALYTE	1992/01/00	1992/07/00	1993/04/00	1993/07/00	1993/09/00
1 Alkalinity (field)			316.000		348.000
2 Bromide			.680	.670	.700
3 Chloride (Cl)			130.000	130.000	140.000
4 Fluoride (F) (Dissol			1.800	2.000	1.900
5 pH (field)			7.080	7.490	7.140
6 Sulfate (SO4)			71.000	68.000	62.000
7 Calcium (Ca) (Dissol			125.000	120.000	130.000
8 Iron (Fe) (Dissolved			.130	1.500	11.000
9 Magnesium (Mg) (Diss			34.000	33.000	33.000
10 Potassium (K) (Disso			7.300	6.900	7.000
11 Sodium (Na) (Dissolv			77.000	78.000	76.000

12	Nitrogen (NPN)			.960	.900	.960
13	Nitrate					
14	Turbidity (NTU)					
15	Ionic Str (PHREEQE)					
16	Carbon (PHREEQE)					
17	Cat/Anion (PHREEQE)					
18	SI Calcite (PHREEQE)					
19	SI Gypsum (PHREEQE)					
20	PCO2, atm (PHREEQE)					
21	Silica (mg/L)					
22	D/H (ppt)					
23	18O/16O (ppt)					

South Fence Well #2

	ANALYTE	1993/12/00	1994/03/00	1994/06/00	1994/09/00	0000/00/00
1	Alkalinity (field)	260.000	334.000			
2	Bromide	.670	-.100			
3	Chloride (Cl)	140.000	140.000			
4	Fluoride (F) (Dissol	2.000	1.900			
5	pH (field)	6.910	6.830			
6	Sulfate (SO4)	74.000	75.000			
7	Calcium (Ca) (Dissol	120.000	120.000			
8	Iron (Fe) (Dissolved	.400	.100			
9	Magnesium (Mg) (Diss	33.000	33.000			
10	Potassium (K) (Disso	6.700	6.500			
11	Sodium (Na) (Dissolv	74.000	73.000			
12	Nitrogen (NPN)	.890	.860			
13	Nitrate					
14	Turbidity (NTU)	3.580	.790			
15	Ionic Str (PHREEQE)		.016			
16	Carbon (PHREEQE)		103.007			
17	Cat/Anion (PHREEQE)		.988			
18	SI Calcite (PHREEQE)		-.036			
19	SI Gypsum (PHREEQE)		-1.611			
20	PCO2, atm (PHREEQE)		-1.250			
21	Silica (mg/L)	14.000	14.000			
22	D/H (ppt)					
23	18O/16O (ppt)					

South Fence Well #3P

	ANALYTE	1993/12/00	1994/03/00	1994/06/00	1994/09/00	0000/00/00
1	Alkalinity (field)	319.000	329.000	313.000	342.000	
2	Bromide	.700	.700	.680	.650	
3	Chloride (Cl)	130.000	140.000	130.000	130.000	
4	Fluoride (F) (Dissol	1.900	1.700	1.600	1.500	
5	pH (field)	6.920	6.850	7.000	6.810	
6	Sulfate (SO4)	99.000	94.000	87.000	83.000	
7	Calcium (Ca) (Dissol	120.000	120.000	120.000	130.000	
8	Iron (Fe) (Dissolved	3.600	.930	1.300	.650	
9	Magnesium (Mg) (Diss	29.000	28.000	28.000	30.000	
10	Potassium (K) (Disso	5.000	4.600	4.600	4.800	
11	Sodium (Na) (Dissolv	92.000	87.000	86.000	87.000	
12	Nitrogen (NPN)	.900	.960	.900	.940	
13	Nitrate					
14	Turbidity (NTU)	71.500	7.000	18.400	5.550	
15	Ionic Str (PHREEQE)		.016			
16	Carbon (PHREEQE)		100.440			
17	Cat/Anion (PHREEQE)		.976			
18	SI Calcite (PHREEQE)		-.027			
19	SI Gypsum (PHREEQE)		-1.513			

20 PCO2, atm (PHREEQE)		-1.277			
21 Silica (mg/L)	15.000	14.000	15.000	14.000	
22 D/H (ppt)				-72.000	
23 18O/16O (ppt)				-10.300	

South Fence Well #3T

ANALYTE	1993/12/00	1994/03/00	1994/06/00	1994/09/00	0000/00/00
1 Alkalinity (field)	16.000	18.000		29.000	
2 Bromide	.550	.590		.560	
3 Chloride (Cl)	47.000	48.000		47.000	
4 Fluoride (F) (Dissol	1.600	.400		.700	
5 pH (field)	7.450	7.770		8.240	
6 Sulfate (SO4)	2200.000	2600.000		2500.000	
7 Calcium (Ca) (Dissol	450.000	450.000		450.000	
8 Iron (Fe) (Dissolved	.020	.060		-.020	
9 Magnesium (Mg) (Diss	41.000	40.000		39.000	
10 Potassium (K) (Disso	5.300	5.200		4.300	
11 Sodium (Na) (Dissolv	500.000	510.000		470.000	
12 Nitrogen (NPN)	-.050	.060		-.050	
13 Nitrate					
14 Turbidity (NTU)	.560	4.410		1.710	
15 Ionic Str (PHREEQE)	.062				
16 Carbon (PHREEQE)	4.049				
17 Cat/Anion (PHREEQE)	1.007				
18 SI Calcite (PHREEQE)	-.530				
19 SI Gypsum (PHREEQE)	-.049				
20 PCO2, atm (PHREEQE)	-3.238				
21 Silica (mg/L)	5.300	5.500		5.100	
22 D/H (ppt)				-92.000	
23 18O/16O (ppt)				-12.400	

SW-TA3 Well

ANALYTE	1992/01/14	1992/07/24	1993/04/00	1993/07/00	1993/09/00
1 Alkalinity (field)	189.500	211.500	207.000	206.000	166.000
2 Bromide	-.100	-.100	.230	.200	.300
3 Chloride (Cl)	31.700	51.200	32.000	31.000	32.000
4 Fluoride (F) (Dissol	1.300	2.100	1.400	1.400	1.400
5 pH (field)	8.100	8.140	8.820	6.490	7.730
6 Sulfate (SO4)	66.000	100.600	46.000	51.000	50.000
7 Calcium (Ca) (Dissol	27.600	23.300	37.000	44.000	50.000
8 Iron (Fe) (Dissolved			1.000	1.500	3.400
9 Magnesium (Mg) (Diss	6.600	6.600	10.000	11.000	12.000
10 Potassium (K) (Disso	4.700	5.600	4.800	5.200	5.700
11 Sodium (Na) (Dissolv	69.100	69.300	69.000	69.000	67.000
12 Nitrogen (NPN)			3.700	3.600	3.700
13 Nitrate	17.100	28.300			
14 Turbidity (NTU)					
15 Ionic Str (PHREEQE)					
16 Carbon (PHREEQE)					
17 Cat/Anion (PHREEQE)					
18 SI Calcite (PHREEQE)					
19 SI Gypsum (PHREEQE)					
20 PCO2, atm (PHREEQE)					
21 Silica (mg/L)					
22 D/H (ppt)					
23 18O/16O (ppt)					

SW-TA3 Well

ANALYTE	1993/12/00	1994/03/00	1994/06/00	1994/09/00	0000/00/00
1 Alkalinity (field)	150.000	177.000	133.000	190.000	

2 Bromide	.250	.220	.190	.200
3 Chloride (Cl)	30.000	30.000	32.000	23.000
4 Fluoride (F) (Dissol	1.500	1.400	1.400	1.300
5 pH (field)	8.150	7.840	7.860	8.200
6 Sulfate (SO4)	48.000	48.000	50.000	42.000
7 Calcium (Ca) (Dissol	41.000	41.000	42.000	45.000
8 Iron (Fe) (Dissolved	1.600	.930	.500	.960
9 Magnesium (Mg) (Diss	11.000	11.000	10.000	11.000
10 Potassium (K) (Disso	5.300	6.800	4.500	4.800
11 Sodium (Na) (Dissolv	61.000	65.000	55.000	55.000
12 Nitrogen (NPN)	3.700	3.600	3.700	3.800
13 Nitrate				
14 Turbidity (NTU)	3.530	31.900	13.500	20.800
15 Ionic Str (PHREEQE)				.007
16 Carbon (PHREEQE)				45.294
17 Cat/Anion (PHREEQE)				1.068
18 SI Calcite (PHREEQE)				.730
19 SI Gypsum (PHREEQE)				-2.108
20 PCO2, atm (PHREEQE)				-2.861
21 Silica (mg/L)		15.000	-.200	15.000
22 D/H (ppt)				-66.000
23 18O/16O (ppt)				-9.800

Tijeras East Well

ANALYTE	1992/01/24	1992/08/03	1993/04/00	1993/07/00	1993/09/00
1 Alkalinity (field)	191.500	144.500	183.000	230.000	209.000
2 Bromide	-.100	-.100	.170	.160	.190
3 Chloride (Cl)	17.000	4.200	11.000	12.000	13.000
4 Fluoride (F) (Dissol	1.200	-.100	.300	.300	.300
5 pH (field)	7.860	7.240	7.560	7.260	7.420
6 Sulfate (SO4)	82.200	35.200	76.000	75.000	85.000
7 Calcium (Ca) (Dissol	66.600	58.700	77.000	78.000	77.000
8 Iron (Fe) (Dissolved			.100	.020	.020
9 Magnesium (Mg) (Diss	9.900	9.600	11.000	11.000	10.000
10 Potassium (K) (Disso	-.200	1.900	1.800	1.800	1.600
11 Sodium (Na) (Dissolv	25.300	26.100	27.000	28.000	25.000
12 Nitrogen (NPN)			2.800	2.900	3.100
13 Nitrate	13.400	4.700			
14 Turbidity (NTU)					
15 Ionic Str (PHREEQE)					
16 Carbon (PHREEQE)					
17 Cat/Anion (PHREEQE)					
18 SI Calcite (PHREEQE)					
19 SI Gypsum (PHREEQE)					
20 PCO2, atm (PHREEQE)					
21 Silica (mg/L)					
22 D/H (ppt)					
23 18O/16O (ppt)					

Tijeras East Well

ANALYTE	1993/12/00	1994/03/00	1994/06/00	1994/09/00	0000/00/00
1 Alkalinity (field)	139.000	208.000	175.000	194.000	
2 Bromide	.170	.140	.150	.140	
3 Chloride (Cl)	14.000	14.000	11.000	13.000	
4 Fluoride (F) (Dissol	.300	.400	.300	.300	
5 pH (field)	7.240	7.340	7.400	7.280	
6 Sulfate (SO4)	81.000	93.000	66.000	77.000	
7 Calcium (Ca) (Dissol	80.000	82.000	79.000	80.000	
8 Iron (Fe) (Dissolved	.020	-.020	.030	.030	
9 Magnesium (Mg) (Diss	11.000	11.000	11.000	11.000	

10 Potassium (K) (Disso	1.800	1.600	1.900	1.700
11 Sodium (Na) (Dissolv	27.000	27.000	29.000	27.000
12 Nitrogen (NPN)	2.700	2.600	2.800	2.900
13 Nitrate				
14 Turbidity (NTU)	.160	1.200	.630	.890
15 Ionic Str (PHREEQE)		.009		
16 Carbon (PHREEQE)		54.283		
17 Cat/Anion (PHREEQE)		.955		
18 SI Calcite (PHREEQE)		.154		
19 SI Gypsum (PHREEQE)		-1.564		
20 PCO2, atm (PHREEQE)		-1.954		
21 Silica (mg/L)	12.000	11.000	11.000	11.000
22 D/H (ppt)				-78.000
23 18O/16O (ppt)				-10.900

South Fence Well #4T

ANALYTE	1995/03/29
1 Alkalinity (field)	110.000
2 Bromide	1.000
3 Chloride (Cl)	180.000
4 Fluoride (F) (Dissol	3.000
5 pH (field)	7.570
6 Sulfate (SO4)	1900.000
7 Calcium (Ca) (Dissol	57.000
8 Iron (Fe) (Dissolved	.050
9 Magnesium (Mg) (Diss	3.400
10 Potassium (K) (Disso	2.500
11 Sodium (Na) (Dissolv	1200.000
12 Nitrogen (NPN)	0.620
13 Nitrate	
14 Turbidity (NTU)	1.650
15 Ionic Str (PHREEQE)	0.067
16 Carbon (PHREEQE)	27.564
17 Cat/Anion (PHREEQE)	1.196
18 SI Calcite (PHREEQE)	-0.470
19 SI Gypsum (PHREEQE)	-0.956
20 PCO2, atm (PHREEQE)	-2.513
21 Silica (mg/L)	4.800
22 D/H (ppt)	
23 18O/16O (ppt)	

PL-3 Well

ANALYTE	1995/03/30
1 Alkalinity (field)	160.000
2 Bromide	0.200
3 Chloride (Cl)	20.000
4 Fluoride (F) (Dissol	0.300
5 pH (field)	7.160
6 Sulfate (SO4)	70.000
7 Calcium (Ca) (Dissol	59.000
8 Iron (Fe) (Dissolved	.100
9 Magnesium (Mg) (Diss	12.000
10 Potassium (K) (Disso	4.700
11 Sodium (Na) (Dissolv	27.000
12 Nitrogen (NPN)	5.000
13 Nitrate	
14 Turbidity (NTU)	0.890
15 Ionic Str (PHREEQE)	0.007
16 Carbon (PHREEQE)	43.677

17	Cat/Anion (PHREEQE)	1.002
18	SI Calcite (PHREEQE)	-0.255
19	SI Gypsum (PHREEQE)	-1.783
20	PCO2, atm (PHREEQE)	-1.882
21	Silica (mg/L)	16.000
22	D/H (ppt)	
23	18O/16O (ppt)	

TRN-1 Well

	ANALYTE	1995/03/31
1	Alkalinity (field)	610.000
2	Bromide	0.700
3	Chloride (Cl)	130.000
4	Fluoride (F) (Dissol	0.900
5	pH (field)	6.650
6	Sulfate (SO4)	71.000
7	Calcium (Ca) (Dissol	100.000
8	Iron (Fe) (Dissolved	.050
9	Magnesium (Mg) (Diss	52.000
10	Potassium (K) (Disso	9.200
11	Sodium (Na) (Dissolv	160.000
12	Nitrogen (NPN)	0.300
13	Nitrate	
14	Turbidity (NTU)	2.310
15	Ionic Str (PHREEQE)	0.021
16	Carbon (PHREEQE)	209.079
17	Cat/Anion (PHREEQE)	0.948
18	SI Calcite (PHREEQE)	-0.071
19	SI Gypsum (PHREEQE)	-1.769
20	PCO2, atm (PHREEQE)	-0.813
21	Silica (mg/L)	14.000
22	D/H (ppt)	
23	18O/16O (ppt)	

MRN-2 Well

	ANALYTE	1995/04/03
1	Alkalinity (field)	160.000
2	Bromide	0.200
3	Chloride (Cl)	10.000
4	Fluoride (F) (Dissol	0.600
5	pH (field)	7.300
6	Sulfate (SO4)	65.000
7	Calcium (Ca) (Dissol	49.000
8	Iron (Fe) (Dissolved	0.030
9	Magnesium (Mg) (Diss	16.000
10	Potassium (K) (Disso	3.700
11	Sodium (Na) (Dissolv	24.000
12	Nitrogen (NPN)	4.500
13	Nitrate	
14	Turbidity (NTU)	2.100
15	Ionic Str (PHREEQE)	0.007
16	Carbon (PHREEQE)	42.181
17	Cat/Anion (PHREEQE)	1.015
18	SI Calcite (PHREEQE)	-0.190
19	SI Gypsum (PHREEQE)	-1.885
20	PCO2, atm (PHREEQE)	-2.021
21	Silica (mg/L)	14.000
22	D/H (ppt)	
23	18O/16O (ppt)	

TJA-2 Well

	ANALYTE	1995/04/04
1	Alkalinity (field)	110.000
2	Bromide	1.000
3	Chloride (Cl)	72.000
4	Fluoride (F) (Dissol	0.200
5	pH (field)	7.300
6	Sulfate (SO4)	61.000
7	Calcium (Ca) (Dissol	80.000
8	Iron (Fe) (Dissolved	-0.020
9	Magnesium (Mg) (Diss	13.000
10	Potassium (K) (Disso	1.800
11	Sodium (Na) (Dissolv	23.000
12	Nitrogen (NPN)	6.000
13	Nitrate	
14	Turbidity (NTU)	0.340
15	Ionic Str (PHREEQE)	0.008
16	Carbon (PHREEQE)	28.949
17	Cat/Anion (PHREEQE)	1.117
18	SI Calcite (PHREEQE)	-0.151
19	SI Gypsum (PHREEQE)	-1.737
20	PCO2, atm (PHREEQE)	-2.190
21	Silica (mg/L)	11.000
22	D/H (ppt)	
23	180/160 (ppt)	

PL-2 Well

	ANALYTE	1995/04/05
1	Alkalinity (field)	160.000
2	Bromide	0.100
3	Chloride (Cl)	10.000
4	Fluoride (F) (Dissol	0.500
5	pH (field)	7.380
6	Sulfate (SO4)	64.000
7	Calcium (Ca) (Dissol	53.000
8	Iron (Fe) (Dissolved	8.900
9	Magnesium (Mg) (Diss	11.000
10	Potassium (K) (Disso	6.100
11	Sodium (Na) (Dissolv	53.000
12	Nitrogen (NPN)	1.000
13	Nitrate	
14	Turbidity (NTU)	762.000
15	Ionic Str (PHREEQE)	0.007
16	Carbon (PHREEQE)	41.492
17	Cat/Anion (PHREEQE)	1.262
18	SI Calcite (PHREEQE)	-0.081
19	SI Gypsum (PHREEQE)	-1.863
20	PCO2, atm (PHREEQE)	-2.103
21	Silica (mg/L)	36.000
22	D/H (ppt)	
23	180/160 (ppt)	

MRN-1 Well

	ANALYTE	1995/04/11
1	Alkalinity (field)	320.000
2	Bromide	0.200
3	Chloride (Cl)	86.000
4	Fluoride (F) (Dissol	1.000
5	pH (field)	7.040
6	Sulfate (SO4)	130.000

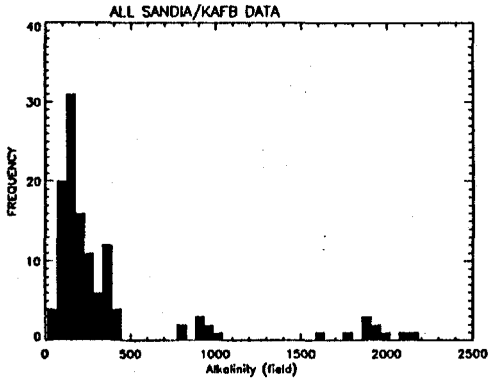
```
 7 Calcium (Ca) (Dissol    150.000
 8 Iron (Fe) (Dissolved     72.000
 9 Magnesium (Mg) (Diss     48.000
10 Potassium (K) (Disso     16.000
11 Sodium (Na) (Dissolv    180.000
12 Nitrogen (NPN)            4.000
13 Nitrate
14 Turbidity (NTU)       +1000.000
15 Ionic Str (PHREEQE)
16 Carbon (PHREEQE)
17 Cat/Anion (PHREEQE)
18 SI Calcite (PHREEQE)
19 SI Gypsum (PHREEQE)
20 PCO2, atm (PHREEQE)
21 Silica (mg/L)           210.000
22 D/H (ppt)
23 18O/16O (ppt)
```

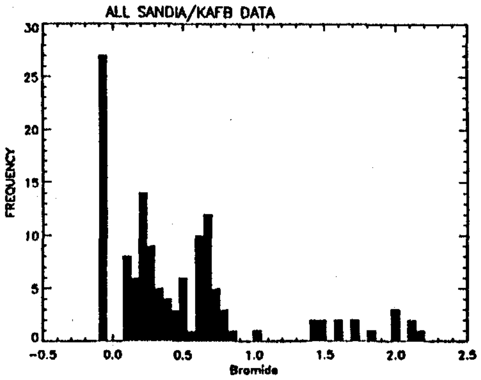
Appendix B

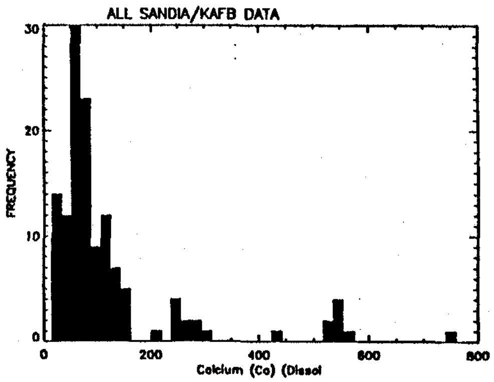
Histograms

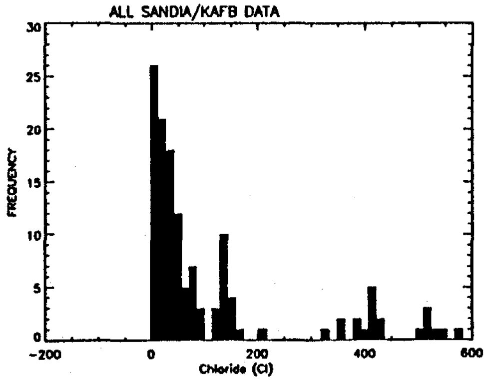
All samples included in sand.dat (Appendix A) were used. Four sets of histograms are included:

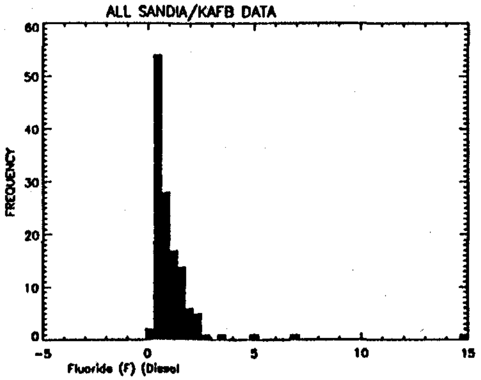
- all wells, linear scale
- all wells, logarithmic scale
- Tsf wells only, linear scale
- Tsf wells only, logarithmic scale

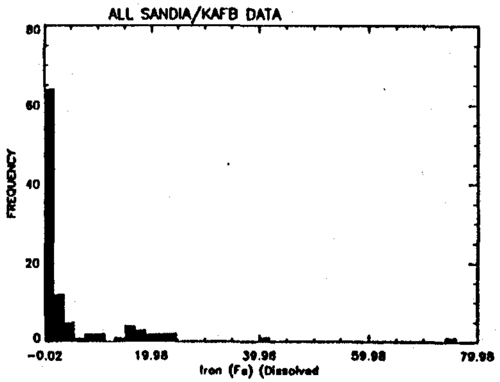

ALL SANDIA/KAFB DATA

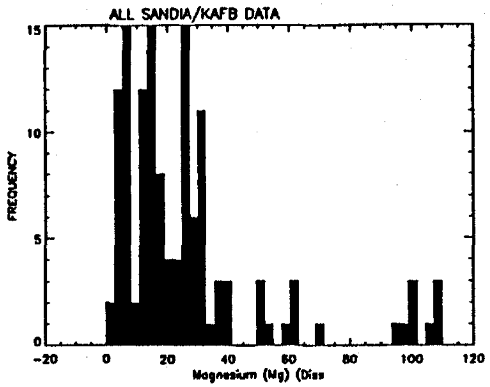

ALL SANDIA/KAFB DATA

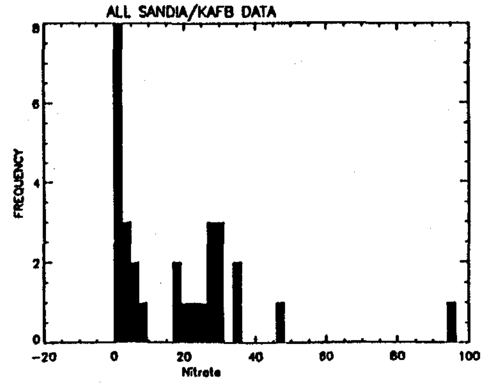

ALL SANDIA/KAFB DATA

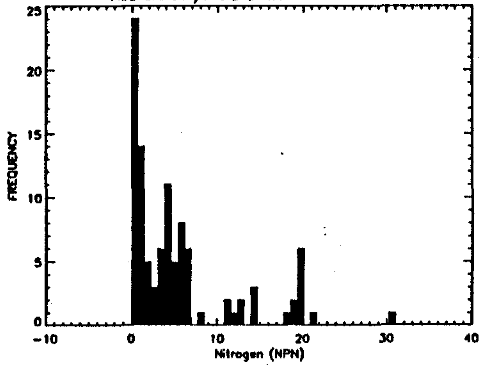

ALL SANDIA/KAFB DATA

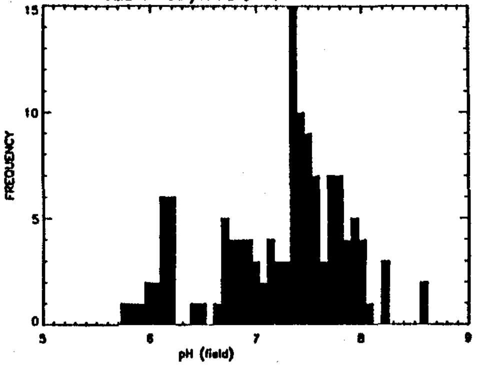

ALL SANDIA/KAFB DATA

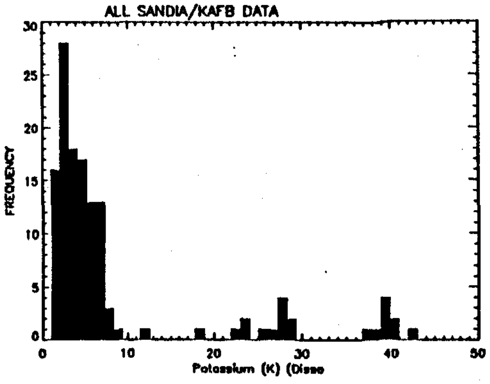

ALL SANDIA/KAFB DATA

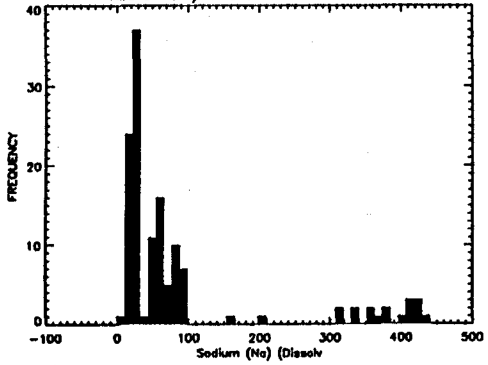

ALL SANDIA/KAFB DATA

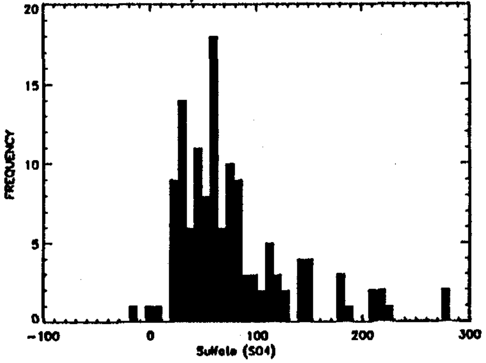

ALL SANDIA/KAFB DATA

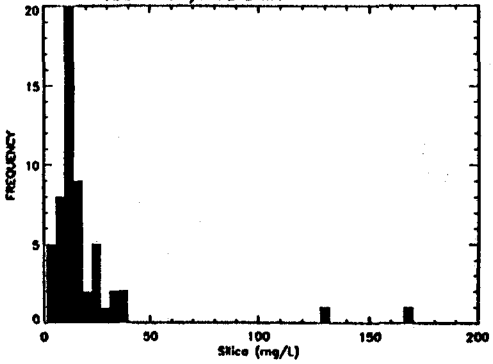

ALL SANDIA/KAFB DATA

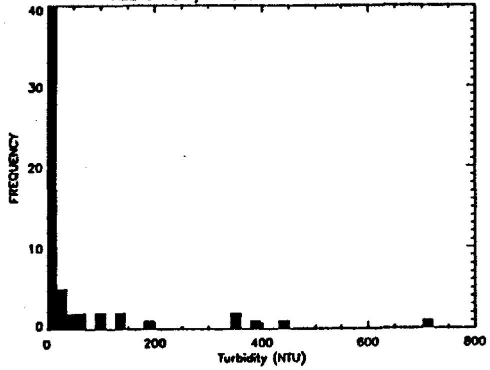

ALL SANDIA/KAFB DATA

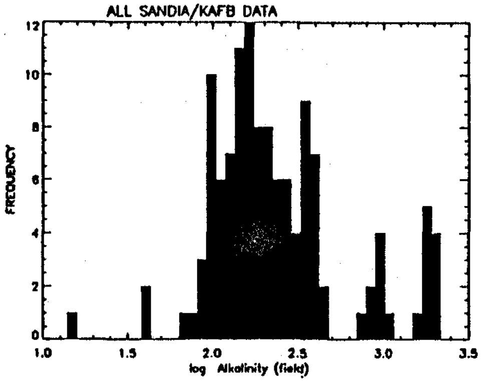

ALL SANDIA/KAFB DATA

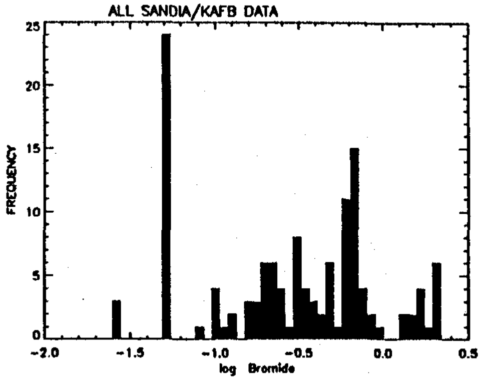

ALL SANDIA/KAFB DATA

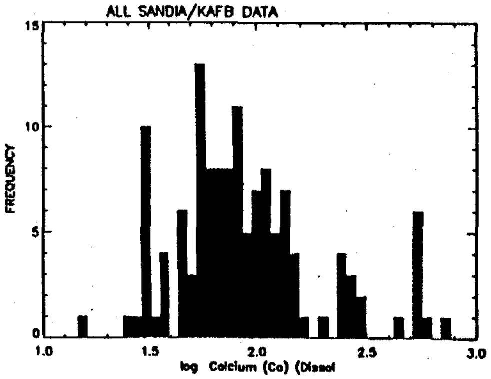

ALL SANDIA/KAFB DATA

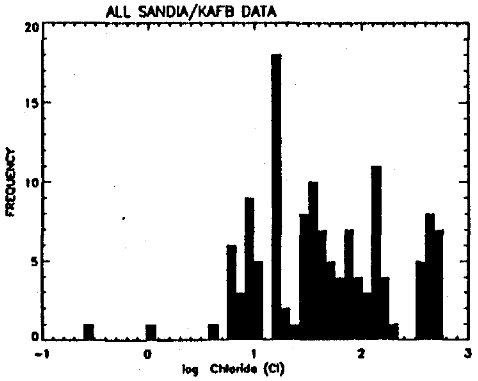

ALL SANDIA/KAFB DATA

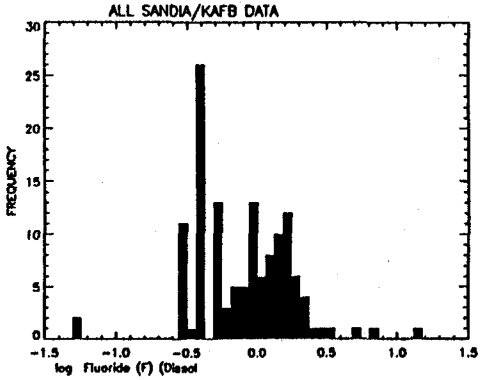

ALL SANDIA/KAFB DATA

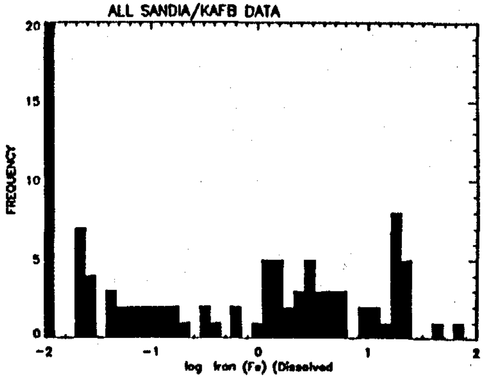

ALL SANDIA/KAFB DATA

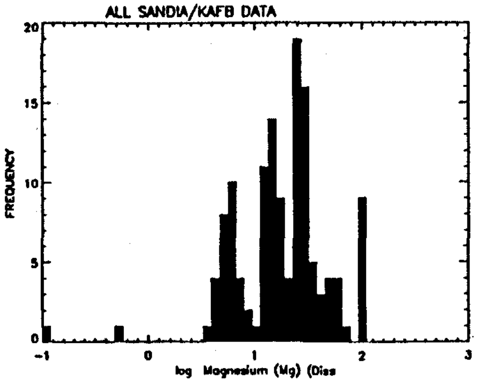

ALL SANDIA/KAFB DATA

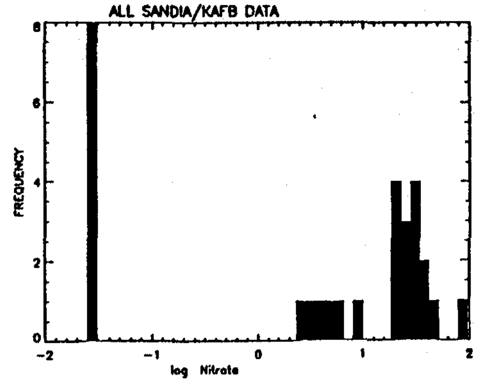

ALL SANDIA/KAFB DATA


ALL SANDIA/KAFB DATA

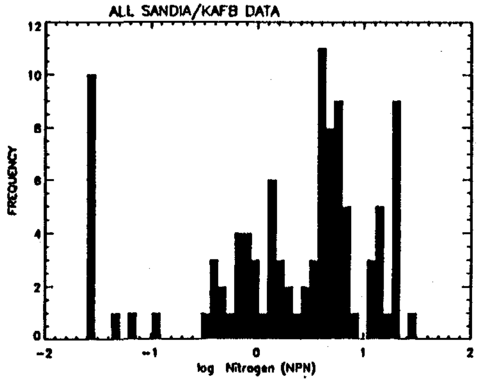

ALL SANDIA/KAFB DATA


ALL SANDIA/KAFB DATA

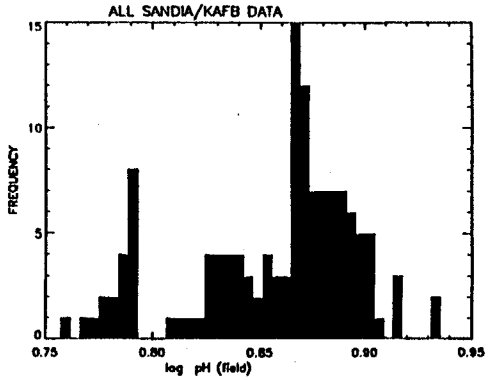

ALL SANDIA/KAFB DATA


ALL SANDIA/KAFB DATA

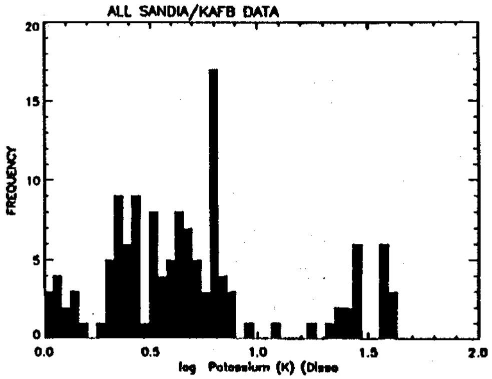
ALL SANDIA/KAFB DATA



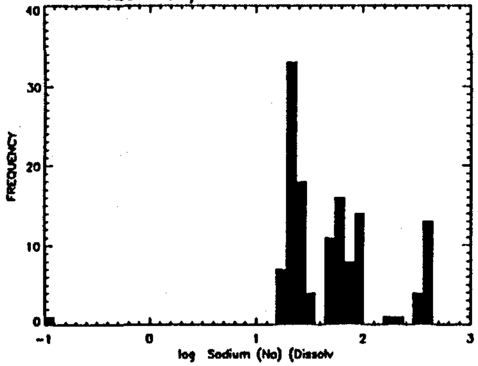
ALL SANDIA/KAFB DATA



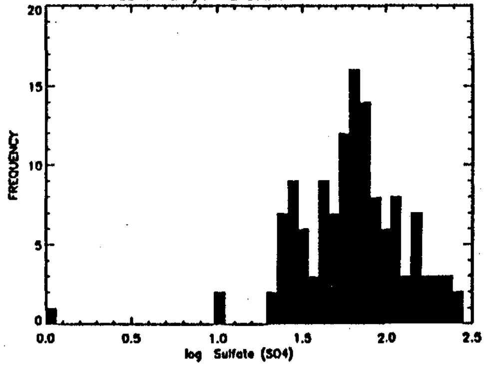
ALL SANDIA/KAFB DATA



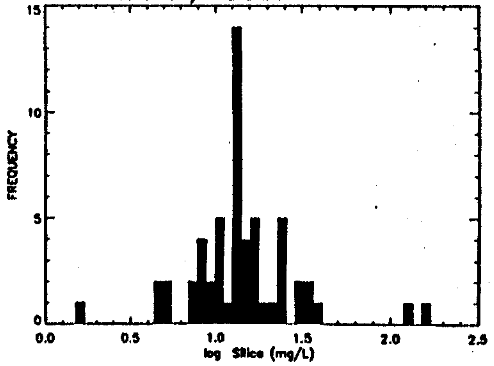
ALL SANDIA/KAFB DATA



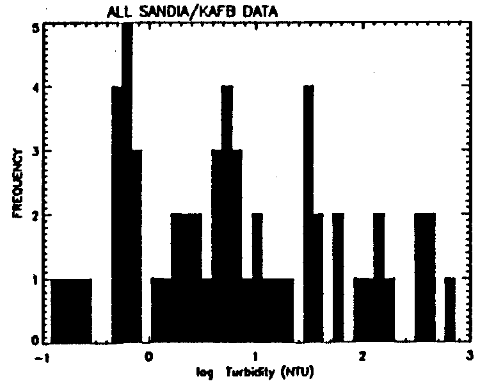
ALL SANDIA/KAFB DATA

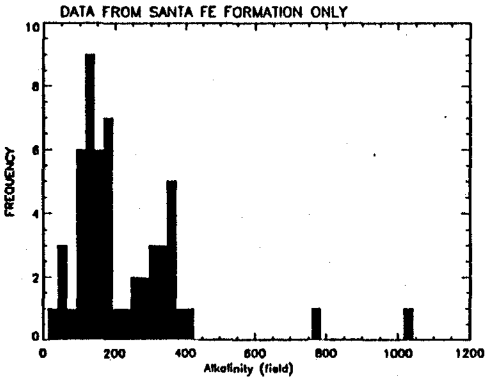


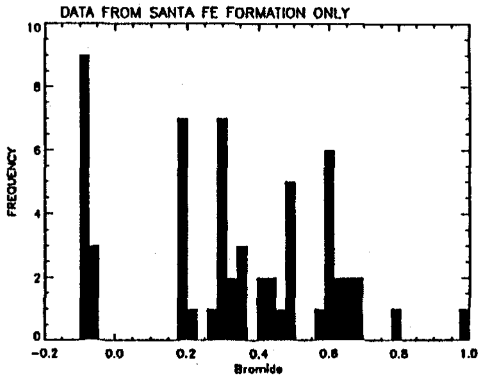
ALL SANDIA/KAFB DATA

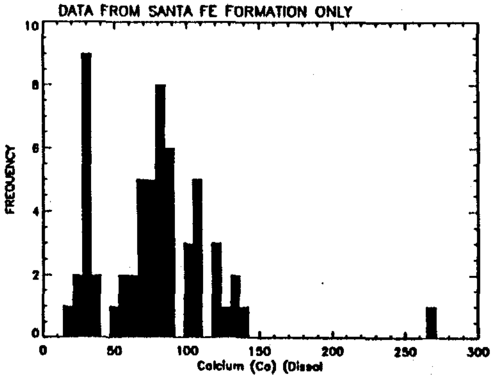


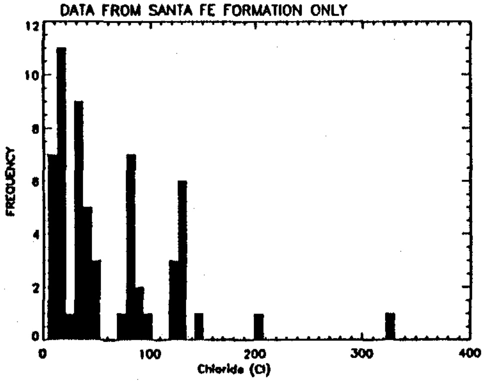
ALL SANDIA/KAFB DATA

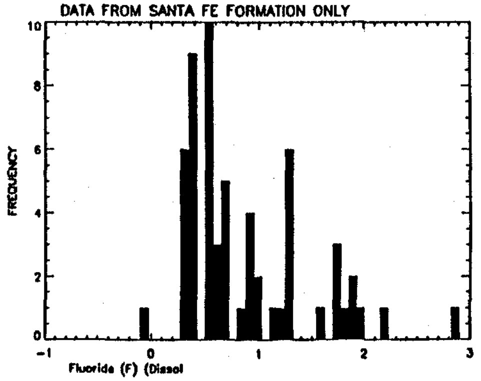


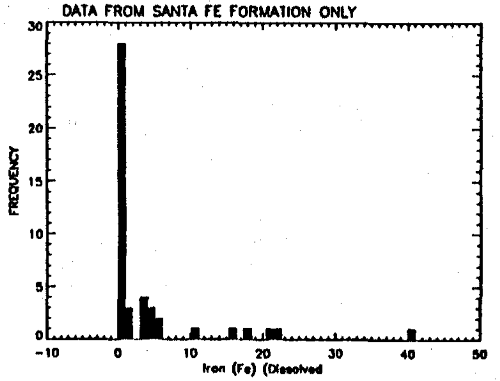

DATA FROM SANTA FE FORMATION ONLY
FREQUENCY
0
2
4
6
8
10
0
200
400
600
800
1000
1200
Alkalinity (field)

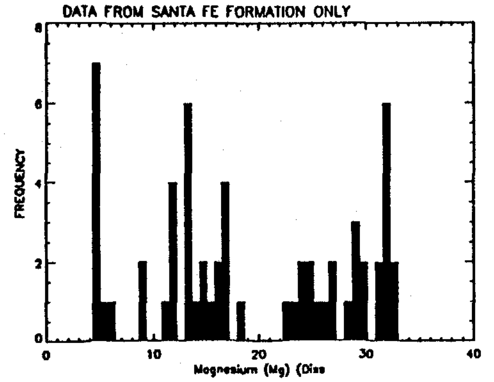

DATA FROM SANTA FE FORMATION ONLY
FREQUENCY
0
2
4
6
8
10
−0.2
0.0
0.2
0.4
0.6
0.8
1.0
Bromide

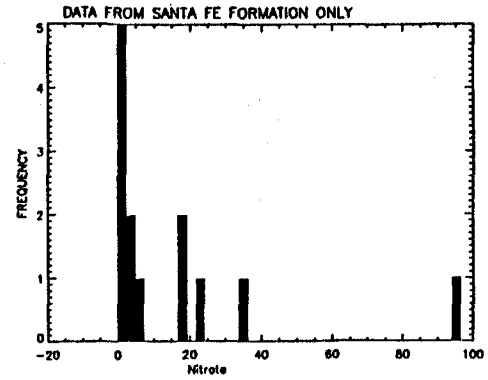

DATA FROM SANTA FE FORMATION ONLY
FREQUENCY
0
2
4
6
8
10
0
50
100
150
200
250
300
Calcium (Ca) (Dissol

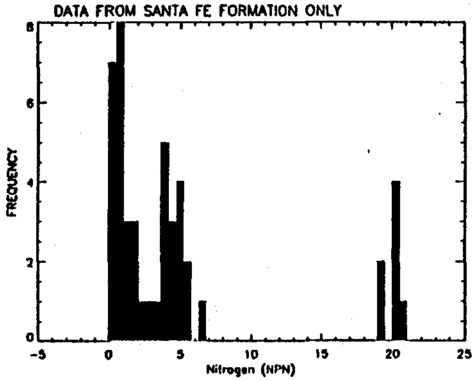

DATA FROM SANTA FE FORMATION ONLY
FREQUENCY
0
2
4
6
8
10
12
0
100
200
300
400
Chloride (Cl)

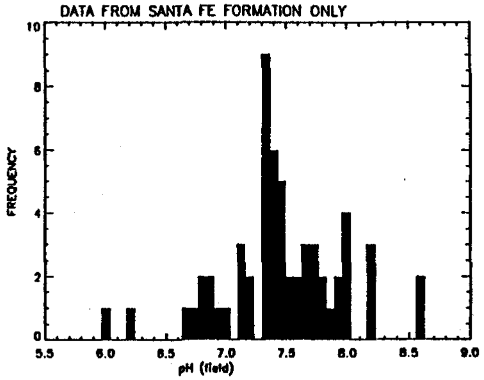

DATA FROM SANTA FE FORMATION ONLY
FREQUENCY
0
2
4
6
8
10
−1
0
1
2
3
Fluoride (F) (Dissol

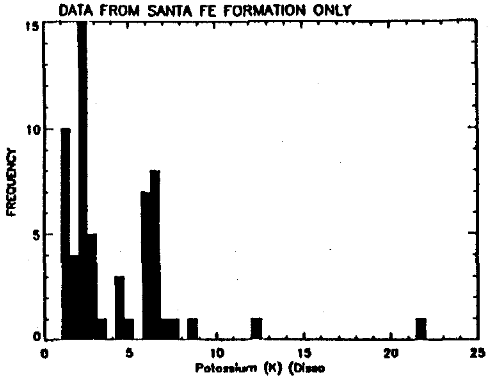

DATA FROM SANTA FE FORMATION ONLY
FREQUENCY
0
5
10
15
20
25
30
−10
0
10
20
30
40
50
Iron (Fe) (Dissolved

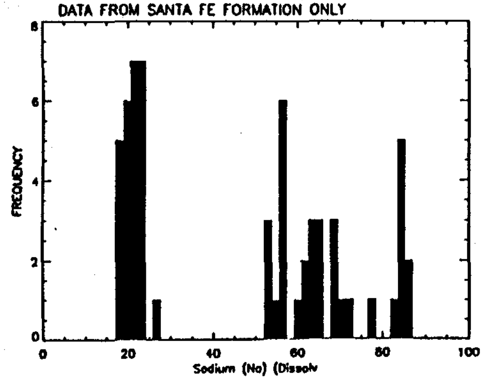

DATA FROM SANTA FE FORMATION ONLY
FREQUENCY
0
2
4
6
8
0
10
20
30
40
Magnesium (Mg) (Diss

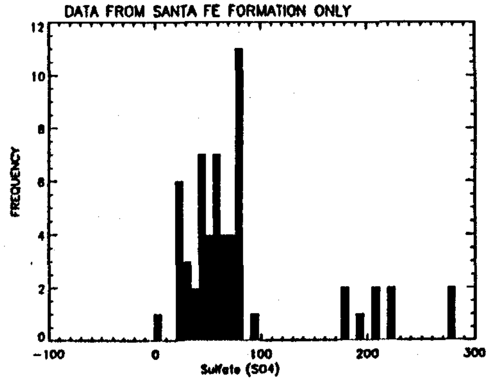

DATA FROM SANTA FE FORMATION ONLY
FREQUENCY
0
1
2
3
4
5
−20
0
20
40
60
80
100
Nitrate

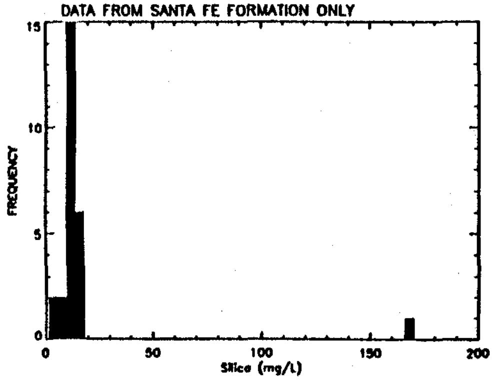

DATA FROM SANTA FE FORMATION ONLY

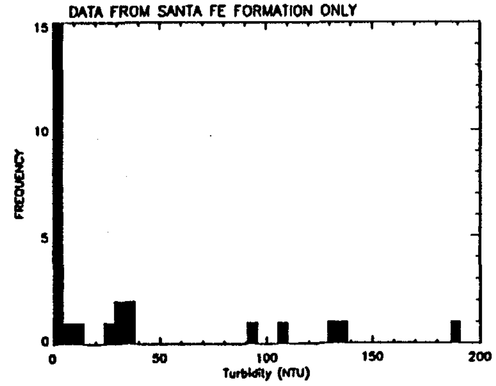

DATA FROM SANTA FE FORMATION ONLY

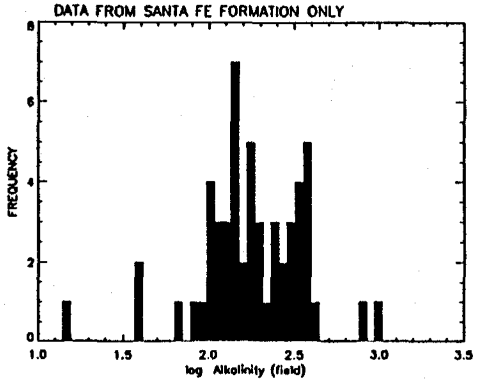

DATA FROM SANTA FE FORMATION ONLY

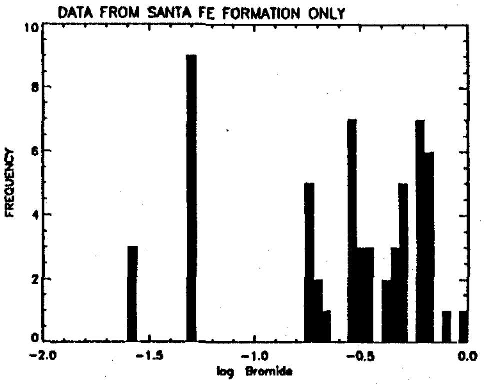

DATA FROM SANTA FE FORMATION ONLY

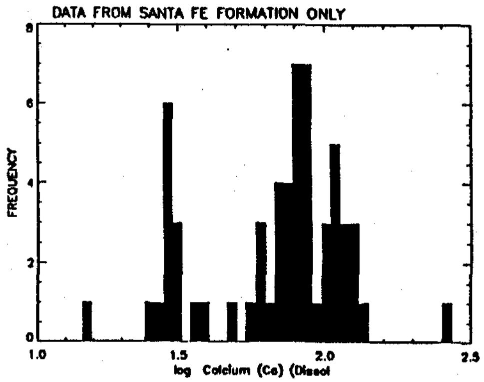

DATA FROM SANTA FE FORMATION ONLY

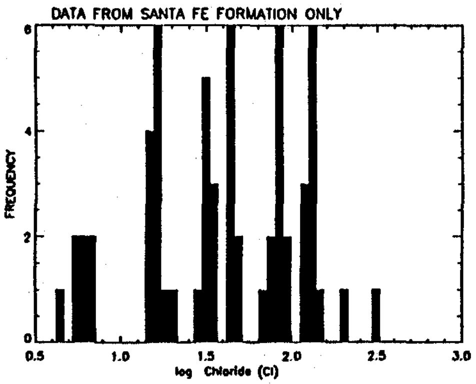

DATA FROM SANTA FE FORMATION ONLY

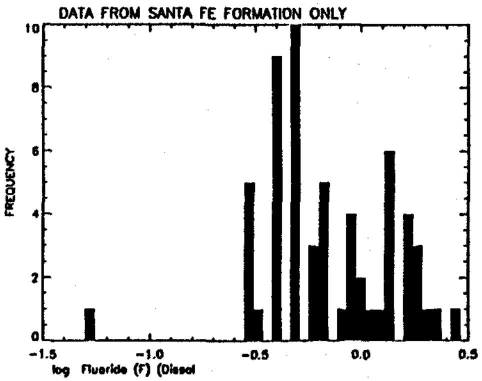

DATA FROM SANTA FE FORMATION ONLY

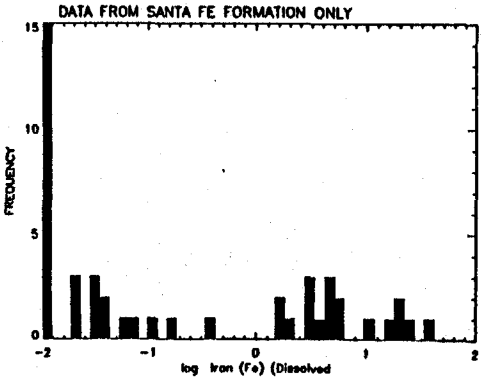

DATA FROM SANTA FE FORMATION ONLY
FREQUENCY
0
2
4
6
8
1.0
1.5
2.0
2.5
3.0
3.5
log Alkalinity (field)

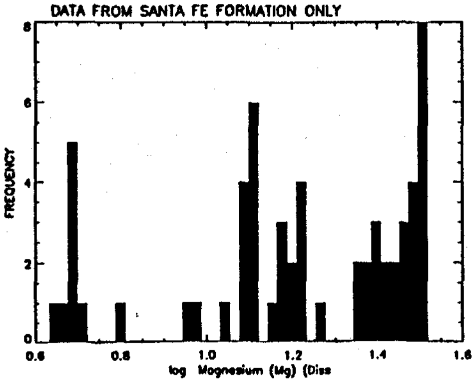

DATA FROM SANTA FE FORMATION ONLY
FREQUENCY
0
2
4
6
8
10
−2.0
−1.5
−1.0
−0.5
0.0
log Bromide

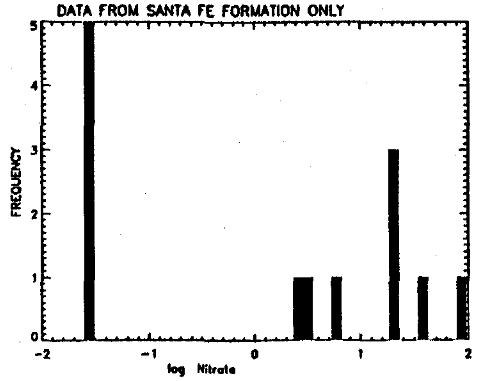

DATA FROM SANTA FE FORMATION ONLY
FREQUENCY
0
2
4
6
8
1.0
1.5
2.0
2.5
log Calcium (Ca) (Dissol

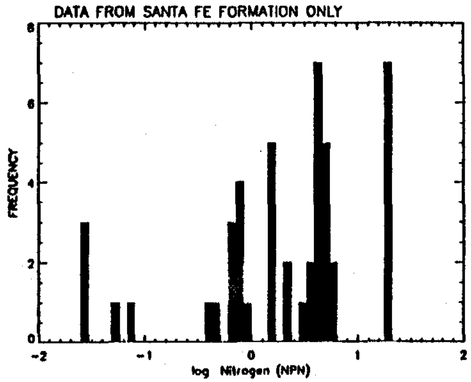

DATA FROM SANTA FE FORMATION ONLY
FREQUENCY
0
2
4
6
0.5
1.0
1.5
2.0
2.5
3.0
log Chloride (Cl)

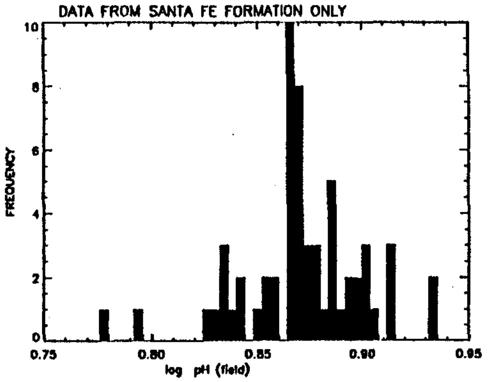

DATA FROM SANTA FE FORMATION ONLY
FREQUENCY
0
2
4
6
8
10
−1.5
−1.0
−0.5
0.0
0.5
log Fluoride (F) (Dissol

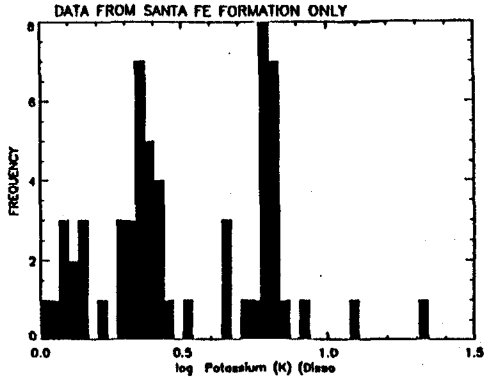

DATA FROM SANTA FE FORMATION ONLY
FREQUENCY
0
5
10
15
−2
−1
0
1
2
log Iron (Fe) (Dissolved

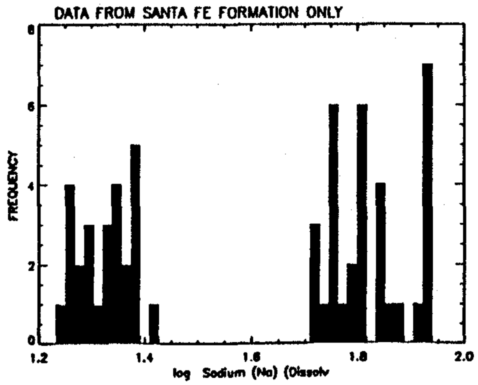

DATA FROM SANTA FE FORMATION ONLY
FREQUENCY
0
2
4
6
8
0.6
0.8
1.0
1.2
1.4
1.6
log Magnesium (Mg) (Diss

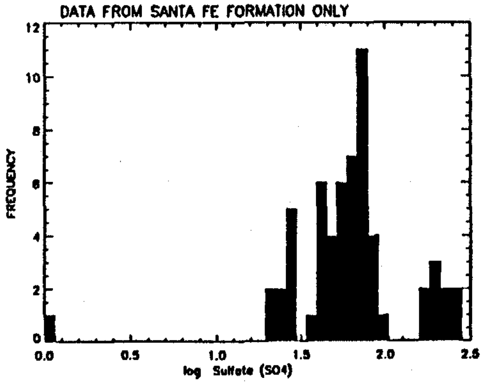

DATA FROM SANTA FE FORMATION ONLY
FREQUENCY
0
1
2
3
4
5
−2
−1
0
1
2
log Nitrate

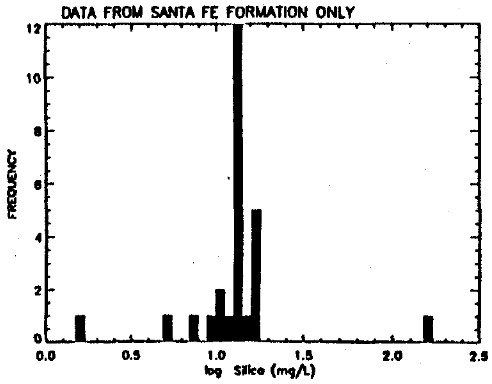

DATA FROM SANTA FE FORMATION ONLY
FREQUENCY
0
2
4
6
8
-2
-1
0
1
2
log Nitrogen (NPN)

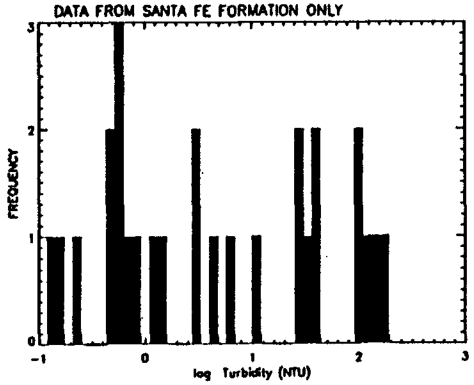

DATA FROM SANTA FE FORMATION ONLY
FREQUENCY
0
2
4
6
8
10
0.75
0.80
0.85
0.90
0.95
log pH (field)


DATA FROM SANTA FE FORMATION ONLY
FREQUENCY
0
2
4
6
8
0.0
0.5
1.0
1.5
log Potassium (K) (Disso


DATA FROM SANTA FE FORMATION ONLY
FREQUENCY
0
2
4
6
8
1.2
1.4
1.6
1.8
2.0
log Sodium (Na) (Dissolv


DATA FROM SANTA FE FORMATION ONLY
FREQUENCY
0
2
4
6
8
10
12
0.0
0.5
1.0
1.5
2.0
2.5
log Sulfate (SO4)


DATA FROM SANTA FE FORMATION ONLY
FREQUENCY
0
2
4
6
8
10
12
0.0
0.5
1.0
1.5
2.0
2.5
log Silica (mg/L)


DATA FROM SANTA FE FORMATION ONLY
FREQUENCY
0
1
2
3
-1
0
1
2
3
log Turbidity (NTU)

Appendix C

Chemical Spot Plots for the Most Representative Data for All Wells and Springs
(in alphabetical order)

Appendix D

Chemical Spot Plots for the Most Representative Data for Wells Screened in the Santa Fe Group (in alphabetical order)

Appendix E

Summary of Mineralogy as Compiled from Well Logs and Thin Section Descriptions

MINERALOGY FROM THE LITHOLOGIC LOGS

BURN SITE WELL
Bedrock
clay
mica schist
quartz
granite

CWL-BW2
Santa Fe Fm
clay
gravel

EOD HILL WELL
Madera LS
carbonate

GOLF COURSE SOUTH WELL
Santa Fe Fm
caliche (near surface)
clay

GREYSTONE WELL
Qal
no log

KAFB-10 WELL
Santa Fe Fm
clay
limestone @1025

LF/DM-01 WELL
Santa Fe Fm
no log

LF/DM-02 WELL
Santa Fe Fm
no log

MVMW-J WELL
Santa Fe Fm
clay

MWL-BW1 WELL
Santa Fe Fm
limestone clasts
caliche (near surface)
quartz
calcareous

NWTA-3 WELL
Santa Fe Fm
caliche (to 200 ft)
calcareous
limestone
clay
granite clasts
oxidized biotite
muscovite
organic blebs? (410 ft)
agate

SCHOOLHOUSE WELL
Qal
no log

SOUTH FENCE WELL #1
Santa Fe Group
clay
limestone
granite
caliche
quartz
feldspar
greenstone
reacts with HCl
arkose
pinkish gray (oxidized?)
grayish green (reduced?)
chert
volcanic ash
obsidian
mafic minerals
black organics
quartzite
dolomitc limestone
decomposed tuff?

SOUTH FENCE WELL #2
Santa Fe Fm
caliche
reaction with HCl
quartz
granite
limestone
clay
quartzite
arkose
feldspar
calcareous sand
meta granite

SOUTH FENCE WELL #3D
Santa Fe Fm
limestone
clay
granite
feldspar
arkose
reaction with HCl
quartzite
caliche
granitic gneiss
silica crystals (167 ft)
biotite
iron oxide stain (265 ft)
chert
petrified wood
greenstone

SOUTH FENCE ROAD #3T
Santa Fe Fm (400 ft - ~520 ft)
limestone
chert
metagranite
quartzite
feldspar
quartz
greenstone
reacts with HCl
CaCO3
arkosic

Fault Zone (520-680 ft)
black organic
slickensides
clay stone
greenish clay streaks
Mn stain
drusy calcite
reaction with HCl
clay
calcite spar
carboniferous shale
limestone
coal?
Fe stain
CaCO3
gypsum? in hairline fractures (583 ft)
gypsum (starts at 583ft)
no reaction with HCl (583 ft)

Lower Tertiary (680-890 ft)
mudstone
detrital limestone
reaction with HCl
calcite in fractures
arkosic
quartz
few marcasite/pyrite spots (705 ft)
greenish gray

Yeso Fm (890-1151 TD)
abundant gypsum
CaCO3
reaction with HCl
quartz
mafics(?)
limestone
chert
selenite gypsum
satin spar gypsum
brownish to greenish-gray (reduced?)
anhydrite
dolomitic(?) anhydrite

SWTA-3 WELL
Santa Fe Fm
quartz
granite
carboniferous nodules (~200 ft)
volcanic clasts

TIJERAS EAST WELL
Santa Fe Fm
arkosic
sand/gravel (no mineralogy given)