GW - ____________

REPORTS

YEAR(S):

1998 - 1996

EL PASO
NATURAL GAS

RECEIVED
APR 10 1998
OIL CONSERVATION DIVISION

April 9, 1998

Mark Ashley
New Mexico Oil Conservation Division
2040 S. Pacheco
Santa Fe, NM 87505

Dear Mark:

Enclosed are the results of the split samples we collected with you from the water wells near El Paso Natural Gas' Washington Ranch Facility. These sample results are consistent with the results from past years.

Thank you for your assistance in this matter and if you have any questions or need additional information, please call me at (915) 759-2228.

Darrell Campbell
Darrell Campbell
Superintendent
Laboratory Services

SAMPLE KEY

SAMPLE NUMBER: S98-0026 LOCATION: WASHINGTON RANCH
MATRIX: WATER
SAMPLE DESCRIPTION: RATTLESNAKE SPRINGS WELL
S D CONTINUED:
S D CONTINUED:
SAMPLE TIME: 08:30 SAMPLE DATE: 01/27/98

SAMPLE KEY

SAMPLE NUMBER: S98-0027 LOCATION: WASHINGTON RANCH
MATRIX: WATER
SAMPLE DESCRIPTION: J. BALLARD WELL
S D CONTINUED:
S D CONTINUED:
SAMPLE TIME: 09:00 SAMPLE DATE: 01/27/98

SAMPLE KEY

SAMPLE NUMBER: S98-0028 LOCATION: WASHINGTON RANCH
MATRIX: WATER
SAMPLE DESCRIPTION: J. BALLARD WELL - DUPLICATE
S D CONTINUED:
S D CONTINUED:
SAMPLE TIME: 09:05 SAMPLE DATE: 01/27/98

SAMPLE KEY

SAMPLE NUMBER: S98-0029 LOCATION: WASHINGTON RANCH
MATRIX: WATER
SAMPLE DESCRIPTION: EPNG WELL
S D CONTINUED:
S D CONTINUED:
SAMPLE TIME: 10:05 SAMPLE DATE: 01/27/98

SAMPLE KEY

SAMPLE NUMBER: S98-0030 LOCATION: WASHINGTON RANCH
MATRIX: WATER
SAMPLE DESCRIPTION: MILLER HOUSE WELL
S D CONTINUED: (PREVIOUSLY LABELED HOOD)
S D CONTINUED:
SAMPLE TIME: 10:30 SAMPLE DATE: 01/27/98

SAMPLE KEY

SAMPLE NUMBER: S98-0031 LOCATION: WASHINGTON RANCH
MATRIX: WATER
SAMPLE DESCRIPTION: MILLER POND WELL
S D CONTINUED: (PREVIOUSLY LABELED HOOD)
S D CONTINUED:
SAMPLE TIME: 11:00 SAMPLE DATE: 01/27/98

SAMPLE KEY

SAMPLE NUMBER: S98-0032 LOCATION: WASHINGTON RANCH
MATRIX: WATER
SAMPLE DESCRIPTION: BLANK
S D CONTINUED:
S D CONTINUED:
SAMPLE TIME: 12:00 SAMPLE DATE: 01/27/98

SAMPLE KEY

SAMPLE NUMBER: S98-0026 LOCATION: WASHINGTON RANCH
MATRIX: WATER
SAMPLE DESCRIPTION: RATTLESNAKE SPRINGS WELL
S D CONTINUED:
S D CONTINUED:
SAMPLE TIME: 08:30 SAMPLE DATE: 01/27/98

SAMPLE KEY

SAMPLE NUMBER: S98-0027 LOCATION: WASHINGTON RANCH
MATRIX: WATER
SAMPLE DESCRIPTION: J. BALLARD WELL
S D CONTINUED:
S D CONTINUED:
SAMPLE TIME: 09:00 SAMPLE DATE: 01/27/98

SAMPLE KEY

SAMPLE NUMBER: S98-0028 LOCATION: WASHINGTON RANCH
MATRIX: WATER
SAMPLE DESCRIPTION: J. BALLARD WELL - DUPLICATE
S D CONTINUED:
S D CONTINUED:
SAMPLE TIME: 09:05 SAMPLE DATE: 01/27/98

SAMPLE KEY

SAMPLE NUMBER: S98-0029 LOCATION: WASHINGTON RANCH
MATRIX: WATER
SAMPLE DESCRIPTION: EPNG WELL
S D CONTINUED:
S D CONTINUED:
SAMPLE TIME: 10:05 SAMPLE DATE: 01/27/98

SAMPLE KEY

SAMPLE NUMBER: S98-0030 LOCATION: WASHINGTON RANCH
MATRIX: WATER
SAMPLE DESCRIPTION: HOOD HOUSE WELL
S D CONTINUED:
S D CONTINUED:
SAMPLE TIME: 10:30 SAMPLE DATE: 01/27/98

SAMPLE KEY

SAMPLE NUMBER: S98-0031 LOCATION: WASHINGTON RANCH
MATRIX: WATER
SAMPLE DESCRIPTION: HOOD POND WELL
S D CONTINUED:
S D CONTINUED:
SAMPLE TIME: 11:00 SAMPLE DATE: 01/27/98

SAMPLE KEY

SAMPLE NUMBER: S98-0032 LOCATION: WASHINGTON RANCH
MATRIX: WATER
SAMPLE DESCRIPTION: BLANK
S D CONTINUED:
S D CONTINUED:
SAMPLE TIME: 12:00 SAMPLE DATE: 01/27/98

NEL LABORATORIES
Reno • Las Vegas
Phoenix • Burbank

Las Vegas Division
4208 Arcata Way, Suite A • Las Vegas, NV 89030
(702) 657-1010 • Fax: (702) 657-1577
1-888-368-3282

CLIENT: El Paso Natural Gas Company
8645 Railroad Drive
El Paso, TX 79904
ATTN: Darrell Campbell

PROJECT NAME: NA
PROJECT NUMBER: NA

NEL ORDER ID: P9801056

Attached are the analytical results for samples in support of the above referenced project.

Samples submitted for this project were not sampled by NEL Laboratories. Samples were received by NEL in good condition, under chain of custody on 1/28/98.

Samples were analyzed as received.

Where applicable we have included the following quality control data:

Method blank - used to demonstrate absence of contamination or interferences in the analytical process.
Laboratory Control Spike (LCS) - used to demonstrate laboratory ability to perform the method within specifications by spiking representative analytes into a clean matrix.
Surrogates - compounds added to each sample to ensure that the method requirements are met for each individual sample.

Should you have any questions or comments, please feel free to contact our Client Services department at (602) 437-0099.

Fluoride: All fluoride batch QC was within acceptable range however, all fluoride results may be biased low because in recent outside performance samples NEL Las Vegas' results have been below acceptance limits.

Some results have been flagged as follows:

J1 - The batch MS and/or MSD were outside acceptance limits. The batch LCS was acceptable.

Stan Van Wagenen
Laboratory Manager

2/4/98
Date

CERTIFICATIONS:

	Reno	Las Vegas	Burbank
Arizona	AZ0520	AZ0518	AZ0325
California	1707	2002	1192
US Army Corps of Engineers	Certified	Certified	Certified

	Reno	Las Vegas	Burbank
Idaho	Certified	Certified	
Montana	Certified	Certified	
Nevada	NV033	NV052	CA084
Washington			Certified

NEL LABORATORIES

CLIENT:	El Paso Natural Gas Company	CLIENT ID:	**S98-0026**
PROJECT NAME:	NA	DATE SAMPLED:	1/27/98
PROJECT NUMBER:	NA	NEL SAMPLE ID:	P9801056-01

TEST: **Metals**
MATRIX: Aqueous

PARAMETER	**RESULT mg/L**	**REPORTING LIMIT**	**D. F.**	**METHOD**	**DIGESTED**	**ANALYZED**
Calcium	95	0.2mg/L	1	EPA 6010A	1/29/98	1/30/98
Magnesium	27	0.2mg/L	1	EPA 6010A	1/29/98	1/30/98
Potassium	ND	2.mg/L	1	EPA 6010A	1/29/98	1/30/98
Silica	5.6	2.mg/L	1	SM 3111 D	1/29/98	2/1/98
Sodium	5.0	0.5mg/L	1	EPA 6010A	1/29/98	1/30/98

D.F. - Dilution Factor

ND - Not Detected

This report shall not be reproduced except in full, without the written approval of the laboratory.

NEL LABORATORIES

CLIENT:	El Paso Natural Gas Company	CLIENT ID:	**S98-0027**
PROJECT NAME:	NA	DATE SAMPLED:	1/27/98
PROJECT NUMBER:	NA	NEL SAMPLE ID:	P9801056-02

TEST: **Metals**
MATRIX: Aqueous

PARAMETER	RESULT mg/L	REPORTING LIMIT	D. F.	METHOD	DIGESTED	ANALYZED
Calcium	320	0.2mg/L	1	EPA 6010A	1/29/98	1/30/98
Magnesium	36	0.2mg/L	1	EPA 6010A	1/29/98	1/30/98
Potassium	ND	2.mg/L	1	EPA 6010A	1/29/98	1/30/98
Silica	8.6	2.mg/L	1	SM 3111 D	1/29/98	2/1/98
Sodium	10	0.5mg/L	1	EPA 6010A	1/29/98	1/30/98

D.F. - Dilution Factor

ND - Not Detected

This report shall not be reproduced except in full, without the written approval of the laboratory.

NEL LABORATORIES

CLIENT:	El Paso Natural Gas Company	CLIENT ID:	**S98-0028**
PROJECT NAME:	NA	DATE SAMPLED:	1/27/98
PROJECT NUMBER:	NA	NEL SAMPLE ID:	P9801056-03

TEST: **Metals**
MATRIX: Aqueous

PARAMETER	RESULT mg/L	REPORTING LIMIT	D. F.	METHOD	DIGESTED	ANALYZED
Calcium	310	0.2mg/L	1	EPA 6010A	1/29/98	1/30/98
Magnesium	36	0.2mg/L	1	EPA 6010A	1/29/98	1/30/98
Potassium	ND	2.mg/L	1	EPA 6010A	1/29/98	1/30/98
Silica	8.9	2.mg/L	1	SM 3111 D	1/29/98	2/1/98
Sodium	10	0.5mg/L	1	EPA 6010A	1/29/98	1/30/98

D.F. - Dilution Factor

ND - Not Detected

This report shall not be reproduced except in full, without the written approval of the laboratory.

NEL LABORATORIES

CLIENT:	El Paso Natural Gas Company	CLIENT ID:	**S98-0029**
PROJECT NAME:	NA	DATE SAMPLED:	1/27/98
PROJECT NUMBER:	NA	NEL SAMPLE ID:	P9801056-04

TEST: **Metals**
MATRIX: Aqueous

PARAMETER	**RESULT mg/L**	**REPORTING LIMIT**	**D. F.**	**METHOD**	**DIGESTED**	**ANALYZED**
Calcium	71	0.2mg/L	1	EPA 6010A	1/29/98	1/30/98
Magnesium	26	0.2mg/L	1	EPA 6010A	1/29/98	1/30/98
Potassium	ND	2.mg/L	1	EPA 6010A	1/29/98	1/30/98
Silica	6.9	2.mg/L	1	SM 3111 D	1/29/98	2/1/98
Sodium	5.4	0.5mg/L	1	EPA 6010A	1/29/98	1/30/98

D.F. - Dilution Factor

ND - Not Detected

This report shall not be reproduced except in full, without the written approval of the laboratory.

NEL LABORATORIES

CLIENT:	El Paso Natural Gas Company	CLIENT ID:	**S98-0030**
PROJECT NAME:	NA	DATE SAMPLED:	1/27/98
PROJECT NUMBER:	NA	NEL SAMPLE ID:	P9801056-05

TEST: **Metals**
MATRIX: Aqueous

PARAMETER	RESULT mg/L	REPORTING LIMIT	D. F.	METHOD	DIGESTED	ANALYZED
Calcium	70	0.2mg/L	1	EPA 6010A	1/29/98	1/30/98
Magnesium	26	0.2mg/L	1	EPA 6010A	1/29/98	1/30/98
Potassium	ND	2.mg/L	1	EPA 6010A	1/29/98	1/30/98
Silica	7.3	2.mg/L	1	SM 3111 D	1/29/98	2/1/98
Sodium	4.4	0.5mg/L	1	EPA 6010A	1/29/98	1/30/98

D.F. - Dilution Factor

ND - Not Detected

This report shall not be reproduced except in full, without the written approval of the laboratory.

CLIENT: El Paso Natural Gas Company
PROJECT NAME: NA
PROJECT NUMBER: NA

CLIENT ID: **S98-0031**
DATE SAMPLED: 1/27/98
NEL SAMPLE ID: P9801056-06

TEST: **Metals**
MATRIX: Aqueous

PARAMETER	**RESULT mg/L**	**REPORTING LIMIT**	**D. F.**	**METHOD**	**DIGESTED**	**ANALYZED**
Calcium	250	0.2mg/L	1	EPA 6010A	1/29/98	1/30/98
Magnesium	41	0.2mg/L	1	EPA 6010A	1/29/98	1/30/98
Potassium	ND	2.mg/L	1	EPA 6010A	1/29/98	1/30/98
Silica	8.8	2.mg/L	1	SM 3111 D	1/29/98	2/1/98
Sodium	12	0.5mg/L	1	EPA 6010A	1/29/98	1/30/98

D.F. - Dilution Factor

ND - Not Detected

This report shall not be reproduced except in full, without the written approval of the laboratory.

NEL LABORATORIES

CLIENT: El Paso Natural Gas Company
PROJECT NAME: NA
PROJECT NUMBER: NA

CLIENT ID: **S98-0032**
DATE SAMPLED: 1/27/98
NEL SAMPLE ID: P9801056-07

TEST: **Metals**
MATRIX: Aqueous

PARAMETER	RESULT mg/L	REPORTING LIMIT	D. F.	METHOD	DIGESTED	ANALYZED
Calcium	ND	0.2mg/L	1	EPA 6010A	1/29/98	1/30/98
Magnesium	ND	0.2mg/L	1	EPA 6010A	1/29/98	1/30/98
Potassium	ND	2.mg/L	1	EPA 6010A	1/29/98	1/30/98
Silica	ND	2.mg/L	1	SM 3111 D	1/29/98	2/1/98
Sodium	ND	0.5mg/L	1	EPA 6010A	1/29/98	1/30/98

D.F. - Dilution Factor

ND - Not Detected

This report shall not be reproduced except in full, without the written approval of the laboratory.

CLIENT:	El Paso Natural Gas Company	CLIENT ID:	**Method Blank**
PROJECT NAME:	NA	DATE SAMPLED:	NA
PROJECT NUMBER:	NA	NEL SAMPLE ID:	P010561-BLK

TEST: **Metals**

PARAMETER	**RESULT mg/L**	**REPORTING LIMIT**	**D. F.**	**METHOD**	**DIGESTED**	**ANALYZED**
Calcium	ND	0.2 mg/L	1	EPA 6010A	1/29/98	1/30/98
Magnesium	ND	0.2 mg/L	1	EPA 6010A	1/29/98	1/30/98
Potassium	ND	2. mg/L	1	EPA 6010A	1/29/98	1/30/98
Sodium	ND	0.5 mg/L	1	EPA 6010A	1/29/98	1/30/98

D.F. - Dilution Factor

ND - Not Detected

This report shall not be reproduced except in full, without the written approval of the laboratory.

NEL LABORATORIES

CLIENT:	El Paso Natural Gas Company	CLIENT ID:	**Method Blank**
PROJECT NAME:	NA	DATE SAMPLED:	NA
PROJECT NUMBER:	NA	NEL SAMPLE ID:	P01056SI-BLK

TEST: **Metals**

PARAMETER	RESULT mg/L	REPORTING LIMIT	D. F.	METHOD	DIGESTED	ANALYZED
Silica	ND	2. mg/L	1	SM 3111 D	1/29/98	2/1/98

D.F. - Dilution Factor

ND - Not Detected

This report shall not be reproduced except in full, without the written approval of the laboratory.

NEL LABORATORIES

CLIENT: El Paso Natural Gas Company	CLIENT ID: **S98-0026**
PROJECT NAME: NA	DATE SAMPLED: 1/27/98
PROJECT NUMBER: NA	NEL SAMPLE ID: P9801056-01

TEST: **Inorganic Non-Metals**
MATRIX: Aqueous

PARAMETER	RESULT	UNITS	REPORTING LIMIT	D. F.	METHOD	ANALYZED
pH	7.31	pH Units	NA	1	EPA 150.1	1/28/98
pH Temperature	20.8	°C	1.	1	EPA 150.1	1/28/98
Specific Conductance	644	µS/cm	1.	1	SM 2510 B	1/29/98
Total Dissolved Solids	404	mg/L	25.	1	SM 2540 C	1/28/98
Hardness, Total (as CaCO3)	360	mg/L	25.	5	SM 2340 C	1/29/98
Alkalinity, Total	200	mg/L	25.	1	SM 2320 B	1/28/98
Alkalinity - Hydroxide	ND	mg/L	25.	1	SM 2320 B	1/28/98
Alkalinity - Carbonate	ND	mg/L	25.	1	SM 2320 B	1/28/98
Alkalinity - Bicarbonate	200	mg/L	25.	1	SM 2320 B	1/28/98
Fluoride	ND	mg/L	1.	10	EPA 300.0	1/28/98
Chloride	4.1	mg/L	1.	10	EPA 300.0	1/28/98
Bromide	ND	mg/L	1.	10	EPA 300	2/4/98
Sulfate	95	mg/L	1.	10	EPA 300.0	1/28/98
Nitrate, as N	0.7	mg/L-N	0.5	10	EPA 300.0	1/28/98
Sulfide	0.033	mg/L	0.02	1	SM 4500-S	1/29/98

D.F. - Dilution Factor
ND - Not Detected

This report shall not be reproduced except in full, without the written approval of the laboratory.

NEL LABORATORIES

CLIENT: El Paso Natural Gas Company
PROJECT NAME: NA
PROJECT NUMBER: NA

CLIENT ID: **S98-0027**
DATE SAMPLED: 1/27/98
NEL SAMPLE ID: P9801056-02

TEST: **Inorganic Non-Metals**
MATRIX: Aqueous

PARAMETER	RESULT	UNITS	REPORTING LIMIT	D. F.	METHOD	ANALYZED
pH	6.99	pH Units	NA	1	EPA 150.1	1/28/98
pH Temperature	20.4	°C	1.	1	EPA 150.1	1/28/98
Specific Conductance	1500	µS/cm	1.	1	SM 2510 B	1/29/98
Total Dissolved Solids	1220	mg/L	25.	1	SM 2540 C	1/28/98
Hardness, Total (as CaCO3)	870	mg/L	25.	5	SM 2340 C	1/29/98
Alkalinity, Total	180	mg/L	25.	1	SM 2320 B	1/28/98
Alkalinity - Hydroxide	ND	mg/L	25.	1	SM 2320 B	1/28/98
Alkalinity - Carbonate	ND	mg/L	25.	1	SM 2320 B	1/28/98
Alkalinity - Bicarbonate	180	mg/L	25.	1	SM 2320 B	1/28/98
Fluoride	ND	mg/L	1.	10	EPA 300.0	1/28/98
Chloride	6.9	mg/L	1.	10	EPA 300.0	1/28/98
Bromide	ND	mg/L	1.	10	EPA 300	2/4/98
Sulfate	620	mg/L	25.	250	EPA 300.0	2/2/98
Nitrate, as N	ND	mg/L-N	0.5	10	EPA 300.0	1/28/98
Sulfide	0.093	mg/L	0.02	1	SM 4500-S	1/29/98

D.F. - Dilution Factor

ND - Not Detected

This report shall not be reproduced except in full, without the written approval of the laboratory.

NEL LABORATORIES

CLIENT: El Paso Natural Gas Company
PROJECT NAME: NA
PROJECT NUMBER: NA

CLIENT ID: **S98-0028**
DATE SAMPLED: 1/27/98
NEL SAMPLE ID: P9801056-03

TEST: **Inorganic Non-Metals**
MATRIX: Aqueous

PARAMETER	RESULT	UNITS	REPORTING LIMIT	D. F.	METHOD	ANALYZED
pH	7.00	pH Units	NA	1	EPA 150.1	1/28/98
pH Temperature	19.8	°C	1.	1	EPA 150.1	1/28/98
Specific Conductance	1490	µS/cm	1.	1	SM 2510 B	1/29/98
Total Dissolved Solids	1230	mg/L	25.	1	SM 2540 C	1/28/98
Hardness, Total (as CaCO3)	890	mg/L	25.	5	SM 2340 C	1/29/98
Alkalinity, Total	190	mg/L	25.	1	SM 2320 B	1/28/98
Alkalinity - Hydroxide	ND	mg/L	25.	1	SM 2320 B	1/28/98
Alkalinity - Carbonate	ND	mg/L	25.	1	SM 2320 B	1/28/98
Alkalinity - Bicarbonate	190	mg/L	25.	1	SM 2320 B	1/28/98
Fluoride	ND	mg/L	1.	10	EPA 300.0	1/28/98
Chloride	6.9	mg/L	1.	10	EPA 300.0	1/28/98
Bromide	ND	mg/L	1.	10	EPA 300	2/4/98
Sulfate	540	mg/L	25.	250	EPA 300.0	2/2/98
Nitrate, as N	ND	mg/L-N	0.5	10	EPA 300.0	1/28/98
Sulfide	0.034	mg/L	0.02	1	SM 4500-S	1/29/98

D.F. - Dilution Factor

ND - Not Detected

This report shall not be reproduced except in full, without the written approval of the laboratory.

NEL LABORATORIES

CLIENT: El Paso Natural Gas Company
PROJECT NAME: NA
PROJECT NUMBER: NA

CLIENT ID: **S98-0029**
DATE SAMPLED: 1/27/98
NEL SAMPLE ID: P9801056-04

TEST: **Inorganic Non-Metals**
MATRIX: Aqueous

PARAMETER	RESULT	UNITS	REPORTING LIMIT	D. F.	METHOD	ANALYZED
pH	7.37	pH Units	NA	1	EPA 150.1	1/28/98
pH Temperature	20.6	°C	1.	1	EPA 150.1	1/28/98
Specific Conductance	503	µS/cm	1.	1	SM 2510 B	1/29/98
Total Dissolved Solids	265	mg/L	25.	1	SM 2540 C	1/28/98
Hardness, Total (as CaCO3)	250	mg/L	25.	5	SM 2340 C	1/29/98
Alkalinity, Total	220	mg/L	25.	1	SM 2320 B	1/28/98
Alkalinity - Hydroxide	ND	mg/L	25.	1	SM 2320 B	1/28/98
Alkalinity - Carbonate	ND	mg/L	25.	1	SM 2320 B	1/28/98
Alkalinity - Bicarbonate	220	mg/L	25.	1	SM 2320 B	1/28/98
Fluoride	ND	mg/L	1.	10	EPA 300.0	1/28/98
Chloride	4.8	mg/L	1.	10	EPA 300.0	1/28/98
Bromide	ND	mg/L	1.	10	EPA 300	2/4/98
Sulfate	28	mg/L	1.	10	EPA 300.0	1/28/98
Nitrate, as N	0.9	mg/L-N	0.5	10	EPA 300.0	1/28/98
Sulfide	ND	mg/L	0.02	1	SM 4500-S	1/29/98

D.F. - Dilution Factor

ND - Not Detected

This report shall not be reproduced except in full, without the written approval of the laboratory.

NEL LABORATORIES

CLIENT: El Paso Natural Gas Company
PROJECT NAME: NA
PROJECT NUMBER: NA

CLIENT ID: **S98-0030**
DATE SAMPLED: 1/27/98
NEL SAMPLE ID: P9801056-05

TEST: **Inorganic Non-Metals**
MATRIX: Aqueous

PARAMETER	RESULT	UNITS	REPORTING LIMIT	D. F.	METHOD	ANALYZED
pH	7.42	pH Units	NA	1	EPA 150.1	1/28/98
pH Temperature	19.7	°C	1.	1	EPA 150.1	1/28/98
Specific Conductance	520	µS/cm	1.	1	SM 2510 B	1/29/98
Total Dissolved Solids	270	mg/L	25.	1	SM 2540 C	1/28/98
Hardness, Total (as CaCO3)	280	mg/L	25.	5	SM 2340 C	1/29/98
Alkalinity, Total	220	mg/L	25.	1	SM 2320 B	1/28/98
Alkalinity - Hydroxide	ND	mg/L	25.	1	SM 2320 B	1/28/98
Alkalinity - Carbonate	ND	mg/L	25.	1	SM 2320 B	1/28/98
Alkalinity - Bicarbonate	220	mg/L	25.	1	SM 2320 B	1/28/98
Fluoride	ND	mg/L	1.	10	EPA 300.0	1/28/98
Chloride	4.0	mg/L	1.	10	EPA 300.0	1/28/98
Bromide	ND	mg/L	1.	10	EPA 300	2/4/98
Sulfate	28	mg/L	1.	10	EPA 300.0	1/28/98
Nitrate, as N	0.9	mg/L-N	0.5	10	EPA 300.0	1/28/98
Sulfide	0.021	mg/L	0.02	1	SM 4500-S	1/29/98

D.F. - Dilution Factor

ND - Not Detected

This report shall not be reproduced except in full, without the written approval of the laboratory.

CLIENT: El Paso Natural Gas Company
PROJECT NAME: NA
PROJECT NUMBER: NA

CLIENT ID: **S98-0031**
DATE SAMPLED: 1/27/98
NEL SAMPLE ID: P9801056-06

TEST: **Inorganic Non-Metals**
MATRIX: Aqueous

PARAMETER	RESULT	UNITS	REPORTING LIMIT	D. F.	METHOD	ANALYZED
pH	7.11	pH Units	NA	1	EPA 150.1	1/28/98
pH Temperature	19.5	°C	1.	1	EPA 150.1	1/28/98
Specific Conductance	1320	µS/cm	1.	1	SM 2510 B	1/29/98
Total Dissolved Solids	1020	mg/L	25.	1	SM 2540 C	1/28/98
Hardness, Total (as CaCO3)	810	mg/L	25.	5	SM 2340 C	1/29/98
Alkalinity, Total	200	mg/L	25.	1	SM 2320 B	1/28/98
Alkalinity - Hydroxide	ND	mg/L	25.	1	SM 2320 B	1/28/98
Alkalinity - Carbonate	ND	mg/L	25.	1	SM 2320 B	1/28/98
Alkalinity - Bicarbonate	200	mg/L	25.	1	SM 2320 B	1/28/98
Fluoride	ND	mg/L	1.	10	EPA 300.0	1/28/98
Chloride	6.6	mg/L	1.	10	EPA 300.0	1/28/98
Bromide	ND	mg/L	1.	10	EPA 300	2/4/98
Sulfate	570 J1	mg/L	10.	100	EPA 300.0	2/4/98
Nitrate, as N	0.7	mg/L-N	0.5	10	EPA 300.0	1/28/98
Sulfide	0.022	mg/L	0.02	1	SM 4500-S	1/29/98

D.F. - Dilution Factor

ND - Not Detected

This report shall not be reproduced except in full, without the written approval of the laboratory.

NEL LABORATORIES

CLIENT: El Paso Natural Gas Company	CLIENT ID: **S98-0032**
PROJECT NAME: NA	DATE SAMPLED: 1/27/98
PROJECT NUMBER: NA	NEL SAMPLE ID: P9801056-07

TEST: **Inorganic Non-Metals**
MATRIX: Aqueous

PARAMETER	RESULT	UNITS	REPORTING LIMIT	D. F.	METHOD	ANALYZED
pH	5.83	pH Units	NA	1	EPA 150.1	1/28/98
pH Temperature	20.8	°C	1.	1	EPA 150.1	1/28/98
Specific Conductance	1.34	µS/cm	1.	1	SM 2510 B	1/29/98
Total Dissolved Solids	ND	mg/L	25.	1	SM 2540 C	1/28/98
Hardness, Total (as CaCO3)	ND	mg/L	5.	1	SM 2340 C	1/29/98
Alkalinity, Total	ND	mg/L	25.	1	SM 2320 B	1/28/98
Alkalinity - Hydroxide	ND	mg/L	25.	1	SM 2320 B	1/28/98
Alkalinity - Carbonate	ND	mg/L	25.	1	SM 2320 B	1/28/98
Alkalinity - Bicarbonate	ND	mg/L	25.	1	SM 2320 B	1/28/98
Fluoride	ND	mg/L	1.	10	EPA 300.0	1/28/98
Chloride	ND	mg/L	1.	10	EPA 300.0	1/28/98
Bromide	ND	mg/L	0.1	1	EPA 300	2/4/98
Sulfate	ND	mg/L	1.	10	EPA 300.0	1/28/98
Nitrate, as N	ND	mg/L-N	0.5	10	EPA 300.0	1/28/98
Sulfide	0.021	mg/L	0.02	1	SM 4500-S	1/29/98

D.F. - Dilution Factor

ND - Not Detected

This report shall not be reproduced except in full, without the written approval of the laboratory.

EL PASO NATURAL GAS

P9801056 2/4

CHAIN OF CUSTODY RECORD

Custody Seal Intact? Y N [✓ None] Temp. 4°C LVlead

Condition when received [✓ good]

Page 1 of 1

PROJECT NUMBER	PROJECT NAME				TOTAL NUMBER OF CONTAINERS	COMPOSITE OR GRAB	REQUESTED ANALYSIS						CONTRACT LABORATORY NEL
SAMPLERS: (Signature) Daniel Campbell			DATE: 1/27/98				Fluoride Nitrate Alkalinity	Bromide Chloride Sulfate	Ca, Mg, K, Na, Si	Total Hardness	pH/Conductance TDS	Sulfide	
LAB ID	DATE	TIME	MATRIX	SAMPLE NUMBER									REMARKS
01	1/27/98	0830	Water	S98-0026	5	G	X	X	X	X	X	X	
02	↓	0900	↓	S98-0027	↓	↓	↓	↓	↓	↓	↓	↓	
03	↓	0905	↓	S98-0028	↓	↓	↓	↓	↓	↓	↓	↓	
04	↓	1005	↓	S98-0029	↓	↓	↓	↓	↓	↓	↓	↓	
05	↓	1030	↓	S98-0030	↓	↓	↓	↓	↓	↓	↓	↓	
06	↓	1100	↓	S98-0031	↓	↓	↓	↓	↓	↓	↓	↓	
07	↓	1200	↓	S98-0032	↓	↓	↓	↓	↓	↓	↓	↓	

RELINQUISHED BY: (Signature) Daniel Campbell	DATE/TIME 1/27/98 1830	RECEIVED BY: (Signature) Fed Ex	RELINQUISHED BY: (Signature) Fed Ex	DATE/TIME 1/28/98 955	RECEIVED BY: (Signature)
RELINQUISHED BY: (Signature)	DATE/TIME	RECEIVED BY: (Signature)	RELINQUISHED BY: (Signature)	DATE/TIME	RECEIVED OF LABORATORY BY: (Signature)

REQUESTED TURNAROUND TIME:

☒ ROUTINE ☐ RUSH

SAMPLE RECEIPT REMARKS

RESULTS & INVOICES TO:

TECHNICAL SERVICES DIVISION LABORATORY
EL PASO NATURAL GAS COMPANY
8645 RAILROAD DRIVE
EL PASO, TEXAS 79904

915-759-2229 FAX: 915-759-2335

CARRIER CO.

CHARGE CODE

BILL NO.:

White - *Testing Laboratory* Canary - *EPNG Lab* Pink - *Field Sampler*

FM-08-0566 (Rev. 12-96)

TRANSMISSION OPERATIONS LABORATORY SAMPLE REPORT

SAMPLE NO.: S98-0026 QA/QC GROUP NO.:

SAMPLE LOCATION: Washington Ranch

SAMPLE SITE DESCRIPTION: Rattlesnake Spring Well

SAMPLE DATE (MM/DD/YY):01/27/98 TIME:08:30

SAMPLE COLLECTED BY: Darrell Campbell

	Analysis Results (mg/l)		Analysis Results (mg/l)
Ammonia (N)	.	Color	.
Chemical Oxygen Demand	.	Fluoride	.
Kjeldahl Nitrogen (N)	.	Iodide	.
Nitrate (N)	.	Odor	.
Nitrite (N)	.	Residue, Total	.
Oil & Grease	.	Residue, Filterable (TDS)	.
Organic Carbon	.	Residue, Nonfilterable (TSS)	.
Orthophosphate (PO_4)	.	Residue, Settleable	.
Phosphorus, Total (P)	.	Residue, Volatile	.
Cyanide, Total	.	Silica	.
Cyanide, Free	.	Specific Conductance (umho)	.
Phenols	.	Sulfate	.
Antimony	.	Sulfite	.
Arsenic	.	Surfactants-MBAS	.
Barium	.	Turbidity NTU	.
Beryllium	.	BHC Isomers	.
Boron	.	Chlordane	.
Cadmium	.	DDT Isomers	.
Calcium	.	Dieldrin	.
Chromium, Total	.	Endrin	.
Chromium, VI	.	Heptachlor	.
Copper	.	Heptachlor Epoxide	.
Hardness ($CaCO_3$)	.	Lindane	.
Iron	.	Methoxychlor	.
Lead	.	Toxaphene	.
Magnesium	.	2,4-D	.
Manganese	.	2,4,5-TP-Silvex	.
Mercury	.	2,4,5-T	.
Nickel	.	Sulfides	.
Potassium	.	Bromoform	.
Selenium	.	Bromodichloromethane	.
Silver	.	Carbon Tetrachloride	.
Sodium	.	Chloroform	.
Thallium	.	Chloromethane	.
Zinc	.	Dibromochloromethane	.
pH	.	Methylene Chloride	.
Acidity, Total	.	Tetrachloroethylene	.
Alkalinity, Total ($CaCO_3$)	.	1,1,1-Trichloroethane	.
Alkalinity, Bicarbonate ($CaCO_3$)	.	Trichloroethylene	.
Bromide	.	Trihalomethanes	.
Carbon Dioxide	.	PCBs ( )	.
Chloride	.	Temperature (°C)	.
Dissolved Oxygen	.	Total Petroleum Hydrocarbons	.

COMMENTS: METHANE - < 0.002 mg/l

ANALYST: Darrell Campbell DATE: 01/30/98

TRANSMISSION OPERATIONS LABORATORY SAMPLE REPORT

SAMPLE NO.: S98-0027 QA/QC GROUP NO.:

SAMPLE LOCATION: Washington Ranch

SAMPLE SITE DESCRIPTION: J. Ballard Well

SAMPLE DATE (MM/DD/YY):01/27/98 TIME:09:00

SAMPLE COLLECTED BY: Darrell Campbell

	Analysis Results (mg/l)		Analysis Results (mg/l)
Ammonia_(N)	.	Color	.
Chemical_Oxygen_Demand	.	Fluoride	.
Kjeldahl_Nitrogen_(N)	.	Iodide	.
Nitrate_(N)	.	Odor	.
Nitrite_(N)	.	Residue,_Total	.
Oil_&_Grease	.	Residue,_Filterable_(TDS)	.
Organic_Carbon	.	Residue,_Nonfilterable_(TSS)	.
Orthophosphate_(PO_4)	.	Residue,_Settleable	.
Phosphorus,_Total_(P)	.	Residue,_Volatile	.
Cyanide,_Total	.	Silica	.
Cyanide,_Free	.	Specific_Conductance_(umho)	.
Phenols	.	Sulfate	.
Antimony	.	Sulfite	.
Arsenic	.	Surfactants-MBAS	.
Barium	.	Turbidity NTU	.
Beryllium	.	BHC_Isomers	.
Boron	.	Chlordane	.
Cadmium	.	DDT_Isomers	.
Calcium	.	Dieldrin	.
Chromium,_Total	.	Endrin	.
Chromium,_VI	.	Heptachlor	.
Copper	.	Heptachlor_Epoxide	.
Hardness_($CaCO_3$)	.	Lindane	.
Iron	.	Methoxychlor	.
Lead	.	Toxaphene	.
Magnesium	.	2,4-D	.
Manganese	.	2,4,5-TP-Silvex	.
Mercury	.	2,4,5-T	.
Nickel	.	Sulfides	.
Potassium	.	Bromoform	.
Selenium	.	Bromodichloromethane	.
Silver	.	Carbon_Tetrachloride	.
Sodium	.	Chloroform	.
Thallium	.	Chloromethane	.
Zinc	.	Dibromochloromethane	.
pH	.	Methylene_Chloride	.
Acidity,_Total	.	Tetrachloroethylene	.
Alkalinity,_Total_($CaCO_3$)	.	1,1,1-Trichloroethane	.
Alkalinity,_Bicarbonate_($CaCO_3$)	.	Trichloroethylene	.
Bromide	.	Trihalomethanes	.
Carbon_Dioxide	.	PCBs______(____)	.
Chloride	.	Temperature_(^{o}C)	.
Dissolved Oxygen	.	Total Petroleum Hydrocarbons	.

COMMENTS: METHANE - 0.480 mg/l
ETHANE - 0.018 mg/l

ANALYST: Darrell Campbell DATE: 01/30/98

TRANSMISSION OPERATIONS LABORATORY SAMPLE REPORT

SAMPLE NO.: S98-0028 QA/QC GROUP NO.:

SAMPLE LOCATION: Washington Ranch

SAMPLE SITE DESCRIPTION: J. Ballard Well - Duplicate

SAMPLE DATE (MM/DD/YY):01/27/98 TIME:09:00

SAMPLE COLLECTED BY: Darrell Campbell

	Analysis Results (mg/l)		Analysis Results (mg/l)
Ammonia_(N)	.	Color	.
Chemical_Oxygen_Demand	.	Fluoride	.
Kjeldahl_Nitrogen_(N)	.	Iodide	.
Nitrate_(N)	.	Odor	.
Nitrite_(N)	.	Residue,_Total	.
Oil_&_Grease	.	Residue,_Filterable_(TDS)	.
Organic_Carbon	.	Residue,_Nonfilterable_(TSS)	.
Orthophosphate_(PO_4)	.	Residue,_Settleable	.
Phosphorus,_Total_(P)	.	Residue,_Volatile	.
Cyanide,_Total	.	Silica	.
Cyanide,_Free	.	Specific_Conductance_(umho)	.
Phenols	.	Sulfate	.
Antimony	.	Sulfite	.
Arsenic	.	Surfactants-MBAS	.
Barium	.	Turbidity NTU	.
Beryllium	.	BHC_Isomers	.
Boron	.	Chlordane	.
Cadmium	.	DDT_Isomers	.
Calcium	.	Dieldrin	.
Chromium,_Total	.	Endrin	.
Chromium,_VI	.	Heptachlor	.
Copper	.	Heptachlor_Epoxide	.
Hardness_($CaCO_3$)	.	Lindane	.
Iron	.	Methoxychlor	.
Lead	.	Toxaphene	.
Magnesium	.	2,4-D	.
Manganese	.	2,4,5-TP-Silvex	.
Mercury	.	2,4,5-T	.
Nickel	.	Sulfides	.
Potassium	.	Bromoform	.
Selenium	.	Bromodichloromethane	.
Silver	.	Carbon_Tetrachloride	.
Sodium	.	Chloroform	.
Thallium	.	Chloromethane	.
Zinc	.	Dibromochloromethane	.
pH	.	Methylene_Chloride	.
Acidity,_Total	.	Tetrachloroethylene	.
Alkalinity,_Total_($CaCO_3$)	.	1,1,1-Trichloroethane	.
Alkalinity,_Bicarbonate_($CaCO_3$)	.	Trichloroethylene	.
Bromide	.	Trihalomethanes	.
Carbon_Dioxide	.	PCBs______(____)	.
Chloride	.	Temperature_(^{O}C)	.
Dissolved Oxygen	.	Total Petroleum Hydrocarbons	.

COMMENTS: METHANE - Sample Lost due to Laboratory Error
ETHANE -

ANALYST: Darrell Campbell DATE: 01/30/98

TRANSMISSION OPERATIONS LABORATORY SAMPLE REPORT

SAMPLE NO.: S98-0029 QA/QC GROUP NO.:

SAMPLE LOCATION: Washington Ranch

SAMPLE SITE DESCRIPTION: EPNG Well

SAMPLE DATE (MM/DD/YY):01/27/98 TIME:10:05

SAMPLE COLLECTED BY: Darrell Campbell

	Analysis Results (mg/l)		Analysis Results (mg/l)
Ammonia_(N)	.	Color	.
Chemical_Oxygen_Demand	.	Fluoride	.
Kjeldahl_Nitrogen_(N)	.	Iodide	.
Nitrate_(N)	.	Odor	.
Nitrite_(N)	.	Residue,_Total	.
Oil_&_Grease	.	Residue,_Filterable_(TDS)	.
Organic_Carbon	.	Residue,_Nonfilterable_(TSS)	.
Orthophosphate_(PO_4)	.	Residue,_Settleable	.
Phosphorus,_Total_(P)	.	Residue,_Volatile	.
Cyanide,_Total	.	Silica	.
Cyanide,_Free	.	Specific_Conductance_(umho)	.
Phenols	.	Sulfate	.
Antimony	.	Sulfite	.
Arsenic	.	Surfactants-MBAS	.
Barium	.	Turbidity NTU	.
Beryllium	.	BHC_Isomers	.
Boron	.	Chlordane	.
Cadmium	.	DDT_Isomers	.
Calcium	.	Dieldrin	.
Chromium,_Total	.	Endrin	.
Chromium,_VI	.	Heptachlor	.
Copper	.	Heptachlor_Epoxide	.
Hardness_($CaCO_3$)	.	Lindane	.
Iron	.	Methoxychlor	.
Lead	.	Toxaphene	.
Magnesium	.	2,4-D	.
Manganese	.	2,4,5-TP-Silvex	.
Mercury	.	2,4,5-T	.
Nickel	.	Sulfides	.
Potassium	.	Bromoform	.
Selenium	.	Bromodichloromethane	.
Silver	.	Carbon_Tetrachloride	.
Sodium	.	Chloroform	.
Thallium	.	Chloromethane	.
Zinc	.	Dibromochloromethane	.
pH	.	Methylene_Chloride	.
Acidity,_Total	.	Tetrachloroethylene	.
Alkalinity,_Total_($CaCO_3$)	.	1,1,1-Trichloroethane	.
Alkalinity,_Bicarbonate_($CaCO_3$)	.	Trichloroethylene	.
Bromide	.	Trihalomethanes	.
Carbon_Dioxide	.	PCBs ( )	.
Chloride	.	Temperature_(°C)	.
Dissolved Oxygen	.	Total Petroleum Hydrocarbons	.

COMMENTS: METHANE - <0.002 mg/l
ETHANE -

ANALYST: Darrell Campbell DATE: 01/30/98

TRANSMISSION OPERATIONS LABORATORY SAMPLE REPORT

SAMPLE NO.: S98-0030 QA/QC GROUP NO.:

SAMPLE LOCATION: Washington Ranch

SAMPLE SITE DESCRIPTION: Miller House Well (Previously labeled Hood)

SAMPLE DATE (MM/DD/YY):01/27/98 TIME:10:30

SAMPLE COLLECTED BY: Darrell Campbell

	Analysis Results (mg/l)		Analysis Results (mg/l)
Ammonia_(N)	.	Color	.
Chemical_Oxygen_Demand	.	Fluoride	.
Kjeldahl_Nitrogen_(N)	.	Iodide	.
Nitrate_(N)	.	Odor	.
Nitrite_(N)	.	Residue,_Total	.
Oil_&_Grease	.	Residue,_Filterable_(TDS)	.
Organic_Carbon	.	Residue,_Nonfilterable_(TSS)	.
Orthophosphate_(PO_4)	.	Residue,_Settleable	.
Phosphorus,_Total_(P)	.	Residue,_Volatile	.
Cyanide,_Total	.	Silica	.
Cyanide,_Free	.	Specific_Conductance_(umho)	.
Phenols	.	Sulfate	.
Antimony	.	Sulfite	.
Arsenic	.	Surfactants-MBAS	.
Barium	.	Turbidity NTU	.
Beryllium	.	BHC_Isomers	.
Boron	.	Chlordane	.
Cadmium	.	DDT_Isomers	.
Calcium	.	Dieldrin	.
Chromium,_Total	.	Endrin	.
Chromium,_VI	.	Heptachlor	.
Copper	.	Heptachlor_Epoxide	.
Hardness_($CaCO_3$)	.	Lindane	.
Iron	.	Methoxychlor	.
Lead	.	Toxaphene	.
Magnesium	.	2,4-D	.
Manganese	.	2,4,5-TP-Silvex	.
Mercury	.	2,4,5-T	.
Nickel	.	Sulfides	.
Potassium	.	Bromoform	.
Selenium	.	Bromodichloromethane	.
Silver	.	Carbon_Tetrachloride	.
Sodium	.	Chloroform	.
Thallium	.	Chloromethane	.
Zinc	.	Dibromochloromethane	.
pH	.	Methylene_Chloride	.
Acidity,_Total	.	Tetrachloroethylene	.
Alkalinity,_Total_($CaCO_3$)	.	1,1,1-Trichloroethane	.
Alkalinity,_Bicarbonate_($CaCO_3$)	.	Trichloroethylene	.
Bromide	.	Trihalomethanes	.
Carbon_Dioxide	.	PCBs ( )	.
Chloride	.	Temperature_(°C)	.
Dissolved Oxygen	.	Total Petroleum Hydrocarbons	.

COMMENTS: METHANE - <0.002 mg/l
ETHANE -

ANALYST: Darrell Campbell DATE: 01/30/98

TRANSMISSION OPERATIONS LABORATORY SAMPLE REPORT

SAMPLE NO.: S98-0031 QA/QC GROUP NO.:

SAMPLE LOCATION: Washington Ranch

SAMPLE SITE DESCRIPTION: Miller Pond Well (Previously labeled Hood)

SAMPLE DATE (MM/DD/YY):01/27/98 TIME:11:00

SAMPLE COLLECTED BY: Darrell Campbell

	Analysis Results (mg/l)		Analysis Results (mg/l)
Ammonia_(N)	.	Color	.
Chemical_Oxygen_Demand	.	Fluoride	.
Kjeldahl_Nitrogen_(N)	.	Iodide	.
Nitrate_(N)	.	Odor	.
Nitrite_(N)	.	Residue,_Total	.
Oil_&_Grease	.	Residue,_Filterable_(TDS)	.
Organic_Carbon	.	Residue,_Nonfilterable_(TSS)	.
Orthophosphate_(PO_4)	.	Residue,_Settleable	.
Phosphorus,_Total_(P)	.	Residue,_Volatile	.
Cyanide,_Total	.	Silica	.
Cyanide,_Free	.	Specific_Conductance_(umho)	.
Phenols	.	Sulfate	.
Antimony	.	Sulfite	.
Arsenic	.	Surfactants-MBAS	.
Barium	.	Turbidity NTU	.
Beryllium	.	BHC_Isomers	.
Boron	.	Chlordane	.
Cadmium	.	DDT_Isomers	.
Calcium	.	Dieldrin	.
Chromium,_Total	.	Endrin	.
Chromium,_VI	.	Heptachlor	.
Copper	.	Heptachlor_Epoxide	.
Hardness_($CaCO_3$)	.	Lindane	.
Iron	.	Methoxychlor	.
Lead	.	Toxaphene	.
Magnesium	.	2,4-D	.
Manganese	.	2,4,5-TP-Silvex	.
Mercury	.	2,4,5-T	.
Nickel	.	Sulfides	.
Potassium	.	Bromoform	.
Selenium	.	Bromodichloromethane	.
Silver	.	Carbon_Tetrachloride	.
Sodium	.	Chloroform	.
Thallium	.	Chloromethane	.
Zinc	.	Dibromochloromethane	.
pH	.	Methylene_Chloride	.
Acidity,_Total	.	Tetrachloroethylene	.
Alkalinity,_Total_($CaCO_3$)	.	1,1,1-Trichloroethane	.
Alkalinity,_Bicarbonate_($CaCO_3$)	.	Trichloroethylene	.
Bromide	.	Trihalomethanes	.
Carbon_Dioxide	.	PCBs ( )	.
Chloride	.	Temperature_(°C)	.
Dissolved Oxygen	.	Total Petroleum Hydrocarbons	.

COMMENTS: METHANE - <0.002 mg/l
ETHANE -

ANALYST: Darrell Campbell DATE: 01/30/98

TRANSMISSION OPERATIONS LABORATORY SAMPLE REPORT

SAMPLE NO.: S98-0032 QA/QC GROUP NO.:

SAMPLE LOCATION: Washington Ranch

SAMPLE SITE DESCRIPTION: Blank

SAMPLE DATE (MM/DD/YY):01/27/98 TIME:12:00

SAMPLE COLLECTED BY: Darrell Campbell

	Analysis Results (mg/l)		Analysis Results (mg/l)
Ammonia_(N)	.	Color	.
Chemical_Oxygen_Demand	.	Fluoride	.
Kjeldahl_Nitrogen_(N)	.	Iodide	.
Nitrate_(N)	.	Odor	.
Nitrite_(N)	.	Residue,_Total	.
Oil_&_Grease	.	Residue,_Filterable_(TDS)	.
Organic_Carbon	.	Residue,_Nonfilterable_(TSS)	.
Orthophosphate_(PO_4)	.	Residue,_Settleable	.
Phosphorus,_Total_(P)	.	Residue,_Volatile	.
Cyanide,_Total	.	Silica	.
Cyanide,_Free	.	Specific_Conductance_(umho)	.
Phenols	.	Sulfate	.
Antimony	.	Sulfite	.
Arsenic	.	Surfactants-MBAS	.
Barium	.	Turbidity NTU	.
Beryllium	.	BHC_Isomers	.
Boron	.	Chlordane	.
Cadmium	.	DDT_Isomers	.
Calcium	.	Dieldrin	.
Chromium,_Total	.	Endrin	.
Chromium,_VI	.	Heptachlor	.
Copper	.	Heptachlor_Epoxide	.
Hardness_($CaCO_3$)	.	Lindane	.
Iron	.	Methoxychlor	.
Lead	.	Toxaphene	.
Magnesium	.	2,4-D	.
Manganese	.	2,4,5-TP-Silvex	.
Mercury	.	2,4,5-T	.
Nickel	.	Sulfides	.
Potassium	.	Bromoform	.
Selenium	.	Bromodichloromethane	.
Silver	.	Carbon_Tetrachloride	.
Sodium	.	Chloroform	.
Thallium	.	Chloromethane	.
Zinc	.	Dibromochloromethane	.
pH	.	Methylene_Chloride	.
Acidity,_Total	.	Tetrachloroethylene	.
Alkalinity,_Total_($CaCO_3$)	.	1,1,1-Trichloroethane	.
Alkalinity,_Bicarbonate_($CaCO_3$)	.	Trichloroethylene	.
Bromide	.	Trihalomethanes	.
Carbon_Dioxide	.	PCBs_____(____)	.
Chloride	.	Temperature_(^{o}C)	.
Dissolved Oxygen	.	Total Petroleum Hydrocarbons	.

COMMENTS: METHANE - <0.002 mg/l
ETHANE -

ANALYST: Darrell Campbell DATE: 01/30/98

El Paso
Natural Gas Company

P. O. BOX 1492
EL PASO, TEXAS 79978
PHONE: 915-541-2600

RECEIVED
MAY 10 1996
OIL CONSERVATION DIVISION

May 6, 1996

Mr. Roger Anderson
Chief, Environmental Bureau
New Mexico Energy, Minerals, and
Natural Resources Dept.
Oil Conservation Division
P. O. Box 6429
Santa Fe, NM 87505-6429

Subject: **Washington Ranch Sampling and Analytical Work Plan**

Dear Mr. Anderson:

Enclosed is El Paso Natural Gas Company's (EPNG) sampling results for the six (6) water wells in the vicinity of the EPNG Washington Ranch Compressor Station. The results do not show any presence of methane in any of the wells except the one Ballard well.

The results were also compared by EPNG scientists to existing water quality data collected in between 1950 to present. It is their opinion that no appreciable change has occurred over this comparison period.

If you have any questions, please contact me at (915) 759-2270.

Sincerely yours,

Donald R. Payne

Donald R. Payne, P. E.
Manager, Compliance Services
Technical Services Division

asg

Enclosure

TRANSMISSION OPERATIONS LABORATORY SAMPLE REPORT

SAMPLE NO.:S96-0081 QA/QC GROUP NO.:Q96-0023

SAMPLE LOCATION: Washington Ranch

SAMPLE SITE DESCRIPTION: Rattle Snake Springs

SAMPLE DATE (MM/DD/YY): 02/22/96 TIME:08:10

SAMPLE COLLECTED BY: John Bennett

	Analysis Results (mg/l)		Analysis Results (mg/l)
Ammonia_(N)	.	Color	.
Chemical_Oxygen_Demand	.	Fluoride	0.2
Kjeldahl_Nitrogen_(N)	.	Iodide	.
Nitrate_(N)	<1.25	Odor	.
Nitrite_(N)	.	Residue,_Total	.
Oil_&_Grease	.	Residue,_Filterable_(TDS)	590.
Organic_Carbon	.	Residue,_Nonfilterable_(TSS)	.
Orthophosphate_(PO_4)	.	Residue,_Settleable	.
Phosphorus,_Total_(P)	.	Residue,_Volatile	.
Cyanide,_Total	.	Silica	9.
Cyanide,_Free	.	Specific_Conductance_(umho)	661.
Phenols	.	Sulfate	141.
Antimony	.	Sulfite	.
Arsenic	.	Surfactants-MBAS	.
Barium	.	Turbidity NTU	.
Beryllium	.	BHC_Isomers	.
Boron	.	Chlordane	.
Cadmium	.	DDT_Isomers	.
Calcium	102.	Dieldrin	.
Chromium,_Total	.	Endrin	.
Chromium,_VI	.	Heptachlor	.
Copper	.	Heptachlor_Epoxide	.
Hardness_($CaCO_3$)	380.	Lindane	.
Iron	.	Methoxychlor	.
Lead	.	Toxaphene	.
Magnesium	30.	2,4-D	.
Manganese	.	2,4,5-TP-Silvex	.
Mercury	.	2,4,5-T	.
Nickel	.	Sulfides	.
Potassium	1.0	Bromoform	.
Selenium	.	Bromodichloromethane	.
Silver	.	Carbon_Tetrachloride	.
Sodium	5.4	Chloroform	.
Thallium	.	Chloromethane	.
Zinc	.	Dibromochloromethane	.
pH	7.44	Methylene_Chloride	.
Acidity,_Total	.	Tetrachloroethylene	.
Alkalinity,_Total_($CaCO_3$)	243.	1,1,1-Trichloroethane	.
Alkalinity,_Bicarbonate_($CaCO_3$)	.	Trichloroethylene	.
Bromide	<1.25	Trihalomethanes	.
Carbon_Dioxide	.	Sulfide___(____)	<1.
Chloride	<10.	Temperature_(°C)	.
Dissolved Oxygen	.	Methane	<0.01

COMMENTS: Coliform not detected

ANALYST: John Bennett DATE: 3/5/96

TRANSMISSION OPERATIONS LABORATORY SAMPLE REPORT

SAMPLE NO.:S96-0082 QA/QC GROUP NO.:Q96-0023

SAMPLE LOCATION: Washington Ranch

SAMPLE SITE DESCRIPTION: J. Ballard Well

SAMPLE DATE (MM/DD/YY): 02/22/96 TIME:08:55

SAMPLE COLLECTED BY: John Bennett

	Analysis Results (mg/l)		Analysis Results (mg/l)
Ammonia_(N)	.	Color	.
Chemical_Oxygen_Demand	.	Fluoride	0.23
Kjeldahl_Nitrogen_(N)	.	Iodide	.
Nitrate_(N)	<1.25	Odor	.
Nitrite_(N)	.	Residue,_Total	.
Oil_&_Grease	.	Residue,_Filterable_(TDS)	1310.
Organic_Carbon	.	Residue,_Nonfilterable_(TSS)	.
Orthophosphate_(PO_4)	.	Residue,_Settleable	.
Phosphorus,_Total_(P)	.	Residue,_Volatile	.
Cyanide,_Total	.	Silica	12.
Cyanide,_Free	.	Specific_Conductance_(umho)	1399.
Phenols	.	Sulfate	698.
Antimony	.	Sulfite	.
Arsenic	.	Surfactants-MBAS	.
Barium	.	Turbidity NTU	.
Beryllium	.	BHC_Isomers	.
Boron	.	Chlordane	.
Cadmium	.	DDT_Isomers	.
Calcium	296.	Dieldrin	.
Chromium,_Total	.	Endrin	.
Chromium,_VI	.	Heptachlor	.
Copper	.	Heptachlor_Epoxide	.
Hardness_($CaCO_3$)	890.	Lindane	.
Iron	.	Methoxychlor	.
Lead	.	Toxaphene	.
Magnesium	37.	2,4-D	.
Manganese	.	2,4,5-TP-Silvex	.
Mercury	.	2,4,5-T	.
Nickel	.	Sulfides	.
Potassium	1.3	Bromoform	.
Selenium	.	Bromodichloromethane	.
Silver	.	Carbon_Tetrachloride	.
Sodium	9.3	Chloroform	.
Thallium	.	Chloromethane	.
Zinc	.	Dibromochloromethane	.
pH	7.26	Methylene_Chloride	.
Acidity,_Total	.	Tetrachloroethylene	.
Alkalinity,_Total_($CaCO_3$)	210.	1,1,1-Trichloroethane	.
Alkalinity,_Bicarbonate_($CaCO_3$)	.	Trichloroethylene	.
Bromide	<1.25	Trihalomethanes	.
Carbon_Dioxide	.	Sulfide___(____)	4.
Chloride	<10.	Temperature_(°C)	.
Dissolved Oxygen	.	Methane	0.71

COMMENTS: Coliform not detected

ANALYST: John Bennett DATE: 3/5/96

TRANSMISSION OPERATIONS LABORATORY SAMPLE REPORT

SAMPLE NO.:S96-0083 QA/QC GROUP NO.:Q96-0023

SAMPLE LOCATION: Washington Ranch

SAMPLE SITE DESCRIPTION: Hood Hand Well

SAMPLE DATE (MM/DD/YY): 02/22/96 TIME:09:15

SAMPLE COLLECTED BY: John Bennett

	Analysis Results (mg/l)		Analysis Results (mg/l)
Ammonia_(N)	.	Color	.
Chemical_Oxygen_Demand	.	Fluoride	0.21
Kjeldahl_Nitrogen_(N)	.	Iodide	.
Nitrate_(N)	<1.25	Odor	.
Nitrite_(N)	.	Residue,_Total	.
Oil_&_Grease	.	Residue,_Filterable_(TDS)	1458.
Organic_Carbon	.	Residue,_Nonfilterable_(TSS)	.
Orthophosphate_(PO_4)	.	Residue,_Settleable	.
Phosphorus,_Total_(P)	.	Residue,_Volatile	.
Cyanide,_Total	.	Silica	16.
Cyanide,_Free	.	Specific_Conductance_(umho)	1520.
Phenols	.	Sulfate	824.
Antimony	.	Sulfite	.
Arsenic	.	Surfactants-MBAS	.
Barium	.	Turbidity NTU	.
Beryllium	.	BHC_Isomers	.
Boron	.	Chlordane	.
Cadmium	.	DDT_Isomers	.
Calcium	340.	Dieldrin	.
Chromium,_Total	.	Endrin	.
Chromium,_VI	.	Heptachlor	.
Copper	.	Heptachlor_Epoxide	.
Hardness_($CaCO_3$)	990.	Lindane	.
Iron	.	Methoxychlor	.
Lead	.	Toxaphene	.
Magnesium	34.	2,4-D	.
Manganese	.	2,4,5-TP-Silvex	.
Mercury	.	2,4,5-T	.
Nickel	.	Sulfides	.
Potassium	1.3	Bromoform	.
Selenium	.	Bromodichloromethane	.
Silver	.	Carbon_Tetrachloride	.
Sodium	8.2	Chloroform	.
Thallium	.	Chloromethane	.
Zinc	.	Dibromochloromethane	.
pH	7.20	Methylene_Chloride	.
Acidity,_Total	.	Tetrachloroethylene	.
Alkalinity,_Total_($CaCO_3$)	192.	1,1,1-Trichloroethane	.
Alkalinity,_Bicarbonate_($CaCO_3$)	.	Trichloroethylene	.
Bromide	<1.25	Trihalomethanes	.
Carbon_Dioxide	.	Sulfide___(____)	<1.
Chloride	<10.	Temperature_(°C)	.
Dissolved Oxygen	.	Methane	<0.01

COMMENTS: Coliform not detected

ANALYST: John Bennett DATE: 3/5/96

TRANSMISSION OPERATIONS LABORATORY SAMPLE REPORT

SAMPLE NO.:S96-0084 QA/QC GROUP NO.:Q96-0023

SAMPLE LOCATION: Washington Ranch

SAMPLE SITE DESCRIPTION: Hood Irrigation Well

SAMPLE DATE (MM/DD/YY): 02/22/96 TIME:09:27

SAMPLE COLLECTED BY: John Bennett

	Analysis Results (mg/l)		Analysis Results (mg/l)
Ammonia_(N)	.	Color	.
Chemical_Oxygen_Demand	.	Fluoride	0.18
Kjeldahl_Nitrogen_(N)	.	Iodide	.
Nitrate_(N)	<1.25	Odor	.
Nitrite_(N)	.	Residue,_Total	.
Oil_&_Grease	.	Residue,_Filterable_(TDS)	1115.
Organic_Carbon	.	Residue,_Nonfilterable_(TSS)	.
Orthophosphate_(PO$_4$)	.	Residue,_Settleable	.
Phosphorus,_Total_(P)	.	Residue,_Volatile	.
Cyanide,_Total	.	Silica	15.
Cyanide,_Free	.	Specific_Conductance_(umho)	1211.
Phenols	.	Sulfate	558.
Antimony	.	Sulfite	.
Arsenic	.	Surfactants-MBAS	.
Barium	.	Turbidity NTU	.
Beryllium	.	BHC_Isomers	.
Boron	.	Chlordane	.
Cadmium	.	DDT_Isomers	.
Calcium	228.	Dieldrin	.
Chromium,_Total	.	Endrin	.
Chromium,_VI	.	Heptachlor	.
Copper	.	Heptachlor_Epoxide	.
Hardness_(CaCO$_3$)	750.	Lindane	.
Iron	.	Methoxychlor	.
Lead	.	Toxaphene	.
Magnesium	44.	2,4-D	.
Manganese	.	2,4,5-TP-Silvex	.
Mercury	.	2,4,5-T	.
Nickel	.	Sulfides	.
Potassium	1.1	Bromoform	.
Selenium	.	Bromodichloromethane	.
Silver	.	Carbon_Tetrachloride	.
Sodium	13.0	Chloroform	.
Thallium	.	Chloromethane	.
Zinc	.	Dibromochloromethane	.
pH	7.20	Methylene_Chloride	.
Acidity,_Total	.	Tetrachloroethylene	.
Alkalinity,_Total_(CaCO$_3$)	210.	1,1,1-Trichloroethane	.
Alkalinity,_Bicarbonate_(CaCO$_3$)	.	Trichloroethylene	.
Bromide	<1.25	Trihalomethanes	.
Carbon_Dioxide	.	Sulfide__(____)	<1.
Chloride	<10.	Temperature_(^{o}C)	.
Dissolved Oxygen	.	Methane	<0.01

COMMENTS: Coliform not detected

ANALYST: John Bennett DATE: 3/5/96

TRANSMISSION OPERATIONS LABORATORY SAMPLE REPORT

SAMPLE NO.:S96-0085 QA/QC GROUP NO.:Q96-0023

SAMPLE LOCATION: Washington Ranch

SAMPLE SITE DESCRIPTION: Hood Domestic Well

SAMPLE DATE (MM/DD/YY): 02/22/96 TIME:09:38

SAMPLE COLLECTED BY: John Bennett

	Analysis Results (mg/l)		Analysis Results (mg/l)
Ammonia_(N)		Color	
Chemical_Oxygen_Demand		Fluoride	0.11
Kjeldahl_Nitrogen_(N)		Iodide	
Nitrate_(N)	<1.25	Odor	
Nitrite_(N)		Residue,_Total	
Oil_&_Grease		Residue,_Filterable_(TDS)	437.
Organic_Carbon		Residue,_Nonfilterable_(TSS)	
Orthophosphate_(PO$_4$)		Residue,_Settleable	
Phosphorus,_Total_(P)		Residue,_Volatile	
Cyanide,_Total		Silica	10.
Cyanide,_Free		Specific_Conductance_(umho)	493.
Phenols		Sulfate	41.
Antimony		Sulfite	
Arsenic		Surfactants-MBAS	
Barium		Turbidity NTU	
Beryllium		BHC_Isomers	
Boron		Chlordane	
Cadmium		DDT_Isomers	
Calcium	69.	Dieldrin	
Chromium,_Total		Endrin	
Chromium,_VI		Heptachlor	
Copper		Heptachlor_Epoxide	
Hardness_(CaCO$_3$)	280.	Lindane	
Iron		Methoxychlor	
Lead		Toxaphene	
Magnesium	26.	2,4-D	
Manganese		2,4,5-TP-Silvex	
Mercury		2,4,5-T	
Nickel		Sulfides	
Potassium	1.0	Bromoform	
Selenium		Bromodichloromethane	
Silver		Carbon_Tetrachloride	
Sodium	4.6	Chloroform	
Thallium		Chloromethane	
Zinc		Dibromochloromethane	
pH	7.55	Methylene_Chloride	
Acidity,_Total		Tetrachloroethylene	
Alkalinity,_Total_(CaCO$_3$)	234.	1,1,1-Trichloroethane	
Alkalinity,_Bicarbonate_(CaCO$_3$)		Trichloroethylene	
Bromide	<1.25	Trihalomethanes	
Carbon_Dioxide		Sulfide___(____)	<1.
Chloride	<10.	Temperature_(^{o}C)	
Dissolved Oxygen		Methane	<0.01

COMMENTS: Coliform TNTC

ANALYST: John Bennett DATE: 3/5/96

TRANSMISSION OPERATIONS LABORATORY SAMPLE REPORT

SAMPLE NO.:S96-0086 QA/QC GROUP NO.:Q96-0023

SAMPLE LOCATION: Washington Ranch

SAMPLE SITE DESCRIPTION: Hood Domestic Well

SAMPLE DATE (MM/DD/YY): 02/22/96 TIME:09:40

SAMPLE COLLECTED BY: John Bennett

	Analysis Results (mg/l)		Analysis Results (mg/l)
Ammonia_(N)		Color	
Chemical_Oxygen_Demand		Fluoride	<0.1
Kjeldahl_Nitrogen_(N)		Iodide	
Nitrate_(N)	<1.25	Odor	
Nitrite_(N)		Residue,_Total	
Oil_&_Grease		Residue,_Filterable_(TDS)	440.
Organic_Carbon		Residue,_Nonfilterable_(TSS)	
Orthophosphate_(PO_4)		Residue,_Settleable	
Phosphorus,_Total_(P)		Residue,_Volatile	
Cyanide,_Total		Silica	11.
Cyanide,_Free		Specific_Conductance_(umho)	494.
Phenols		Sulfate	41.
Antimony		Sulfite	
Arsenic		Surfactants-MBAS	
Barium		Turbidity NTU	
Beryllium		BHC_Isomers	
Boron		Chlordane	
Cadmium		DDT_Isomers	
Calcium	69.	Dieldrin	
Chromium,_Total		Endrin	
Chromium,_VI		Heptachlor	
Copper		Heptachlor_Epoxide	
Hardness_($CaCO_3$)	278.	Lindane	
Iron		Methoxychlor	
Lead		Toxaphene	
Magnesium	26.	2,4-D	
Manganese		2,4,5-TP-Silvex	
Mercury		2,4,5-T	
Nickel		Sulfides	
Potassium	0.8	Bromoform	
Selenium		Bromodichloromethane	
Silver		Carbon_Tetrachloride	
Sodium	4.6	Chloroform	
Thallium		Chloromethane	
Zinc		Dibromochloromethane	
pH	7.55	Methylene_Chloride	
Acidity,_Total		Tetrachloroethylene	
Alkalinity,_Total_($CaCO_3$)	236.	1,1,1-Trichloroethane	
Alkalinity,_Bicarbonate_($CaCO_3$)		Trichloroethylene	
Bromide	<1.25	Trihalomethanes	
Carbon_Dioxide		Sulfide___(____)	<1.
Chloride	<10.	Temperature_(^{O}C)	
Dissolved Oxygen		Methane	<0.01

COMMENTS: Coliform TNTC

ANALYST: John Bennett DATE: 3/5/96

TRANSMISSION OPERATIONS LABORATORY SAMPLE REPORT

SAMPLE NO.:S96-0087 QA/QC GROUP NO.:Q96-0023

SAMPLE LOCATION: Washington Ranch

SAMPLE SITE DESCRIPTION: EPNG Well

SAMPLE DATE (MM/DD/YY): 02/22/96 TIME:10:20

SAMPLE COLLECTED BY: John Bennett

	Analysis Results (mg/l)		Analysis Results (mg/l)
Ammonia_(N)	.	Color	.
Chemical_Oxygen_Demand	.	Fluoride	<0.1
Kjeldahl_Nitrogen_(N)	.	Iodide	.
Nitrate_(N)	<1.25	Odor	.
Nitrite_(N)	.	Residue,_Total	.
Oil_&_Grease	.	Residue,_Filterable_(TDS)	441.
Organic_Carbon	.	Residue,_Nonfilterable_(TSS)	.
Orthophosphate_(PO_4)	.	Residue,_Settleable	.
Phosphorus,_Total_(P)	.	Residue,_Volatile	.
Cyanide,_Total	.	Silica	13.
Cyanide,_Free	.	Specific_Conductance_(umho)	494.
Phenols	.	Sulfate	40.
Antimony	.	Sulfite	.
Arsenic	.	Surfactants-MBAS	.
Barium	.	Turbidity NTU	.
Beryllium	.	BHC_Isomers	.
Boron	.	Chlordane	.
Cadmium	.	DDT_Isomers	.
Calcium	68.	Dieldrin	.
Chromium,_Total	.	Endrin	.
Chromium,_VI	.	Heptachlor	.
Copper	.	Heptachlor_Epoxide	.
Hardness_($CaCO_3$)	278.	Lindane	.
Iron	.	Methoxychlor	.
Lead	.	Toxaphene	.
Magnesium	26.	2,4-D	.
Manganese	.	2,4,5-TP-Silvex	.
Mercury	.	2,4,5-T	.
Nickel	.	Sulfides	.
Potassium	0.9	Bromoform	.
Selenium	.	Bromodichloromethane	.
Silver	.	Carbon_Tetrachloride	.
Sodium	4.5	Chloroform	.
Thallium	.	Chloromethane	.
Zinc	.	Dibromochloromethane	.
pH	7.51	Methylene_Chloride	.
Acidity,_Total	.	Tetrachloroethylene	.
Alkalinity,_Total_($CaCO_3$)	236.	1,1,1-Trichloroethane	.
Alkalinity,_Bicarbonate_($CaCO_3$)	.	Trichloroethylene	.
Bromide	<1.25	Trihalomethanes	.
Carbon_Dioxide	.	Sulfide ( )	<1.
Chloride	<10.	Temperature_($^{\circ}C$)	.
Dissolved Oxygen	.	Methane	<0.01

COMMENTS: Coliform not detected

ANALYST: John Bennett DATE: 3/5/96

GENERAL CHEMISTRY - QUALITY CONTROL

QA/QC GROUP: Q96-0023

PARAMETER	UNITS	SAMPLE RESULT	DUPLICATE RESULT	RPD	SPIKED SAMPLE RESULT	SPIKE CONC.	% REC	SAMPLE RESULT	DUPLICATE RESULT	RPD	SPIKED SAMPLE RESULT	SPIKE CONC.	% REC	BLANK	CHECK STANDARD	CHECK STANDARD RESULT	RPD CHECK STANDARD
pH	UNITS	7.51	7.49	0.3%		NA	NA	7.12	7.12	0.0%		NA	NA	NA	7.38	7.4	0.5%
P ALK ($CaCO_3$)	mg/L					NA	NA					NA	NA	NA			
M ALK ($CaCO_3$)	mg/L	236	237	0.4%		NA	NA	194	195	0.5%		NA	NA	NA	50	52	3.9%
Cl	mg/L	<10	<10	#VALUE!				829	819	1.2%					10	9.73	2.7%
SO_4	mg/L	40	40	0.0%				242	255	5.2%					12.5	12.7	1.6%
TOTAL HARDNESS	mg/L	278	278	0.0%		NA	NA	1240	1220	1.6%		NA	NA	NA			
Ca ($CaCO_3$)	mg/L	69	68	1.5%				800	780	2.5%							
Mg ($CaCO_3$)	mg/L	26	26	0.0%		NA	NA	440	440	0.0%		NA	NA	NA			
Na	mg/L	4.6	4.6	0.0%				190	200	5.1%					5.0	4.9	1.8%
K	mg/L	0.8	0.9	11.8%				9.4	7.9	17.3%					5.0	5.0	0.6%
F	mg/L	<0.1	<0.1	#VALUE!				0.44	0.40	9.5%					1	0.98	2.0%
SiO_2	mg/L	13	12	8.0%				54	50	7.7%					10	9.6	4.1%
TDS	mg/L	441	441	0.0%		NA	NA	1989	1990	0.1%		NA	NA	NA			
SC	mg/L	494	492	0.4%		NA	NA	3100	3100	0.0%		NA	NA	NA			
NO_3	mg/L	<1.25	<1.25	#VALUE!				<1.25	<1.25	#VALUE!					1.25	1.29	2.8%
Br	mg/L	<1.25	<1.25	#VALUE!				<1.25	<1.25	#VALUE!					1.25	1.29	3.4%
F.P.	degree F			#DIV/0!		NA	NA			#DIV/0!		NA	NA	NA	NA	NA	NA
TREATMENT	mg/L					NA	NA					NA	NA	NA	NA	NA	NA
RESERVE ALK.	mg/L					NA	NA					NA	NA	NA	NA	NA	NA

GENERAL CHEMISTRY - QUALITY CONTROL

QA/QC GROUP: Q96-0023

PARAMETER	UNITS	SAMPLE RESULT	DUPLICATE RESULT	RPD	SPIKED SAMPLE RESULT	SPIKE CONC.	% REC	SAMPLE RESULT	DUPLICATE RESULT	RPD	SPIKED SAMPLE RESULT	SPIKE CONC.	% REC	BLANK	CHECK STANDARD	CHECK STANDARD RESULT	RPD CHECK STANDARD
pH	UNITS	7.51	7.49	0.3%		NA	NA	7.12	7.12	0.0%		NA	NA	NA	7.38	7.4	0.5%
P ALK ($CaCO_3$)	mg/L					NA	NA					NA	NA	NA			
M ALK ($CaCO_3$)	mg/L	236	237	0.4%		NA	NA	194	195	0.5%		NA	NA	NA	50	52	3.9%
Cl	mg/L	<10	<10	#VALUE!				829	819	1.2%				0.00	10	9.73	2.7%
SO_4	mg/L	40	40	0.0%				242	255	5.2%				0.00	12.5	12.7	1.6%
TOTAL HARDNESS	mg/L	278	278	0.0%		NA	NA	1240	1220	1.6%		NA	NA	NA			
Ca ($CaCO_3$)	mg/L	69	68	1.5%				800	780	2.5%				0.00			
Mg ($CaCO_3$)	mg/L	26	26	0.0%		NA	NA	440	440	0.0%		NA	NA	NA			
Na	mg/L	4.6	4.6	0.0%				190	200	5.1%				0.06	5.0	4.9	1.8%
K	mg/L	0.8	0.9	11.8%				9.4	7.9	17.3%					5.0	5.0	0.6%
F	mg/L	<0.1	<0.1	#VALUE!				0.44	0.40	9.5%					1	0.98	2.0%
SiO_2	mg/L	13	12	8.0%				54	50	7.7%				0.13	10	9.6	4.1%
TDS	mg/L	441	441	0.0%		NA	NA	1989	1990	0.1%		NA	NA	NA			
SC	mg/L	494	492	0.4%		NA	NA	3100	3100	0.0%		NA	NA	NA			
NO_3	mg/L	<1.25	<1.25	#VALUE!				<1.25	<1.25	#VALUE!				0.00	1.25	1.29	2.8%
Br	mg/L	<1.25	<1.25	#VALUE!				<1.25	<1.25	#VALUE!				0.00	1.25	1.29	3.4%
B	mg/L	0.310	0.243	24.2%		NA	NA	0.184	0.207	11.8%		NA	NA	0.09	1.50	1.59	5.8%
Fe	mg/L	0.40	0.40	0.0%		NA	NA	0.70	1.10	44%		NA	NA	0.07	3.00	3.11	3.6%
Mn	mg/L	<0.1	<0.1	#VALUE!		NA	NA	<0.1	<0.1	#VALUE!		NA	NA	0.01	0.5	0.51	2.0%
Cu	mg/L	<0.1	<0.1	#VALUE!				<0.1	<0.1	#VALUE!				0.02	1.00	0.94	6.2%
Zn	mg/L	<0.1	<0.1	#VALUE!				<0.1	<0.1	#VALUE!				0.00	0.5	0.5	0.0%

El Paso Natural Gas Company

CHAIN OF CUSTODY RECORD

Page 1 of 1

PROJECT NUMBER	PROJECT NAME						CONTRACT LABORATORY P. O. NUMBER El Paso
SAMPLERS: (Signature) Darrell Campbell			DATE: 2/22/96				

LAB ID	DATE	TIME	MATRIX	SAMPLE NUMBER	TOTAL NUMBER OF CONTAINERS	COMPOSITE OR GRAB	Anions + cations	Methane	Sulfide				REMARKS
	2/22/96	0804	Water	S96-0081	2	G	X	X	X				
		0855		S96-0082	2	G	X	X	X				
		0815		S96-0083	2	G	X	X	X				
		0927		S96-0084	2	G	X	X	X				
		0938		S96-0085	2	G	X	X	X				
		0940		S96-0086	2	G	X	X	X				
	↓	1020	↓	S96-0087	2	G	X	X	X				

RELINQUISHED BY: (Signature) Darrell Campbell	DATE/TIME 2/22/96 1400	RECEIVED BY: (Signature)	RELINQUISHED BY: (Signature)	DATE/TIME	RECEIVED BY: (Signature)
RELINQUISHED BY: (Signature)	DATE/TIME	RECEIVED BY: (Signature)	RELINQUISHED BY: (Signature)	DATE/TIME	RECEIVED OF LABORATORY BY: (Signature)

REQUESTED TURNAROUND TIME:
☒ ROUTINE ☐ RUSH

SAMPLE RECEIPT REMARKS

CARRIER CO.

CHARGE CODE

BILL NO.:

RESULTS & INVOICES TO:

TRANSMISSION OPERATIONS LABORATORY
EL PASO NATURAL GAS COMPANY
8645 RAILROAD DRIVE
EL PASO, TEXAS 79904

915-759-2229 FAX: 915-759-2335

White - *Testing Laboratory* Canary - *EPNG Lab* Pink - *Field Sampler*

FM-08-0566 (Rev. 5-95)

American Environmental Network (NM), Inc.
Albuquerque • Phoenix • Pensacola • Portland • Pleasant Hills • Columbia

CHAIN OF CUSTODY

DATE: ________ PAGE: ___ OF ___

AEN LAB I.D.

SHADED AREAS ARE FOR LAB USE ONLY.

PLEASE FILL THIS FORM IN COMPLETELY.

PROJECT MANAGER: [illegible]

COMPANY: [illegible]
ADDRESS: [illegible]
[illegible]
PHONE: [illegible]
FAX: [illegible]
BILL TO: [illegible]
COMPANY: [illegible]
ADDRESS:

ANALYSIS REQUEST

SAMPLE ID	DATE	TIME	MATRIX	LAB I.D.	Petroleum Hydrocarbons (418.1) TRPH	(MOD.8015) Diesel/Direct/Inject		(M8015) Gas/Purge & Trap	Gasoline/BTEX & MTBE (M8015/8020)	BTXE/MTBE (8020)	BTEX & Chlorinated Aromatics (602/8020)	BTEX/MTBE/EDC & EDB (8020/8010/Short)	Chlorinated Hydrocarbons (601/8010)		504 EDB ☐ / DBCP ☐	Polynuclear Aromatics (610/8310)	Volatile Organics (624/8240) GC/MS	Volatile Organics (8260) GC/MS		Pesticides/PCB (608/8080)	Herbicides (615/8150)	Base/Neutral/Acid Compounds GC/MS (625/8270)		General Chemistry: [illegible]	[illegible]		Priority Pollutant Metals (13)	Target Analyte List Metals (23)	RCRA Metals (8)	RCRA Metals by TCLP (Method 1311)	Metals:		NUMBER OF CONTAINERS
[illegible]	[illegible]	[illegible]	[illegible]																					✓	✓								
[illegible] WELL		[illegible]																						✓	✓								
EPNG WELL		[illegible]																						✓	✓								
WOOD [illegible]		[illegible]																						✓	✓								
WOOD POND		[illegible]																						✓	✓								
TRIP BLANK	[illegible]																								✓								
FIELD BLANK																									✓								

PROJECT INFORMATION

PROJ. NO.:
PROJ. NAME: [illegible]
P.O. NO.:
SHIPPED VIA:

SAMPLE RECEIPT

NO. CONTAINERS	
CUSTODY SEALS	Y / N / NA
RECEIVED INTACT	
BLUE ICE/ICE	

PRIOR AUTHORIZATION IS REQUIRED FOR RUSH PROJECTS

(RUSH) ☐ 24hr ☐ 48hr ☐ 72hr ☐ 1 WEEK (NORMAL) ☒
CERTIFICATION REQUIRED: ☐ NM ☐ SDWA ☐ OTHER
METHANOL PRESERVATION ☐
COMMENTS: FIXED FEE ☐

RELINQUISHED BY: 1.
Signature: [illegible] Time: [illegible]
Printed Name: [illegible] Date: [illegible]
Company: [illegible]

RELINQUISHED BY: 2.
Signature: Time:
Printed Name: Date:
Company:

RECEIVED BY: 1.
Signature: Time:
Printed Name: Date:
Company:

RECEIVED BY: (LAB) 2.
Signature: Time:
Printed Name: Date:
American Enviromental Network (NM), Inc.

4/1/96 AEN Inc.: American Environmental Network (NM), Inc. • 2709-D Pan American Freeway, NE • Albuquerque, New Mexico 87107

DISTRIBUTION: White, Canary - AEN Pink - ORIGINATOR

RECEIVED

AUG 21 1989

OIL CONSERVATION DIV.
SANTA FE

Natural Gas Contamination at Rattlesnake Springs, Carlsbad Caverns National Park: Review of the Geohydrology in the Vicinity of Rattlesnake Springs and the Contamination Problem

Report Number 1 of 4

by

Michael Richard, Ph.D.
Department of Environmental Health
Colorado State University

Submitted in partial fulfillment of NPS Contract No. RFQ 7029-8-0025

November 1, 1988

Natural Gas Contamination at Rattlesnake Springs, Carlsbad Caverns National Park: Review of the Geohydrology in the Vicinity of Rattlesnake Springs and the Contamination Problem

Introduction

Carlsbad Caverns National Park (CCNP) relies on one source of potable water, Rattlesnake Springs, located approximately 8 miles south of the park in the upper Black River Valley. The National Park Service (NPS) has water rights to this water dating to the 1880's. Water use at CCNP ranges from 500,000 to 1,000,000 gallons per day to supply a peak visitor load of 10,000 visitors per day and to supply 20-30 year round residences used by NPS personnel. Water is scarce in this area and Rattlesnake Springs represents a unique and probably irreplaceable water resource.

The upper Black River Valley south and west of Rattlesnake Springs was developed in the 1970's as a natural gas field. After this resource was exhausted in 1981, this area was developed as a natural gas reinjection and storage facility, the Washington Ranch Gas Storage Project. By 1984, a total of 23 gas injection/withdrawal wells have been placed in service within two miles of Rattlesnake Springs.

Groundwater contamination appears to have occurred in several water wells near Rattlesnake Springs due to leakage of natural gas from several of the gas injection/withdrawal wells. Elevated concentrations of benzene and polycyclic aromatic hydrocarbons have been documented in the impacted wells along with sulfide contamination and accompanying odor and well corrosion.

At issue is whether these contaminants can move through groundwater to Rattlesnake Springs and impact this water source. Rattlesnake Springs lies approximately 1.25 miles north of the gas reinjection area and in the general path of groundwater flow. The goal of this investigation is to assess the potential for natural gas contamination at Rattlesnake Springs and to suggest appropriate remedial action(s).

Report Contents

This report presents a summary of background information important to an understanding of the natural gas groundwater contamination problem in the upper Black River Valley in the vicinity of Rattlesnake Springs. This report contains a literature review of the geology and hydrology of the area including a bibliography of important resource materials, a history of the groundwater contamination problem, the potential impacts of this contamination at Rattlesnake Springs, and a brief presentation of Colorado State University's activities in this investigation.

Geology of the Upper Black River Valley

The upper Black River Valley is located in the southeast corner of New Mexico near the Texas border. This small valley of approximately 35 miles in length is bordered on the north and northwest by the Guadalupe Mountains which rise 300-700 feet above the valley floor and bordered on the east by the Yeso Hills, shown in Figure 1. Elevations range from 4200 feet above sea level at the southwest end of the valley near the mouth of Slaughter Canyon to 3250 feet at Blue Springs at the northeast end of the valley, a drop in elevation of approximately 25 feet per mile. Rattlesnake Springs is located near the northeast end of the valley at an elevation of 3650 feet. The valley is bordered on the east by the Black River which is generally dry for most of its length. Surface water is present year round only in a limited section of the river near Rattlesnake Springs due to a series of small dams and groundwater discharge in this area.

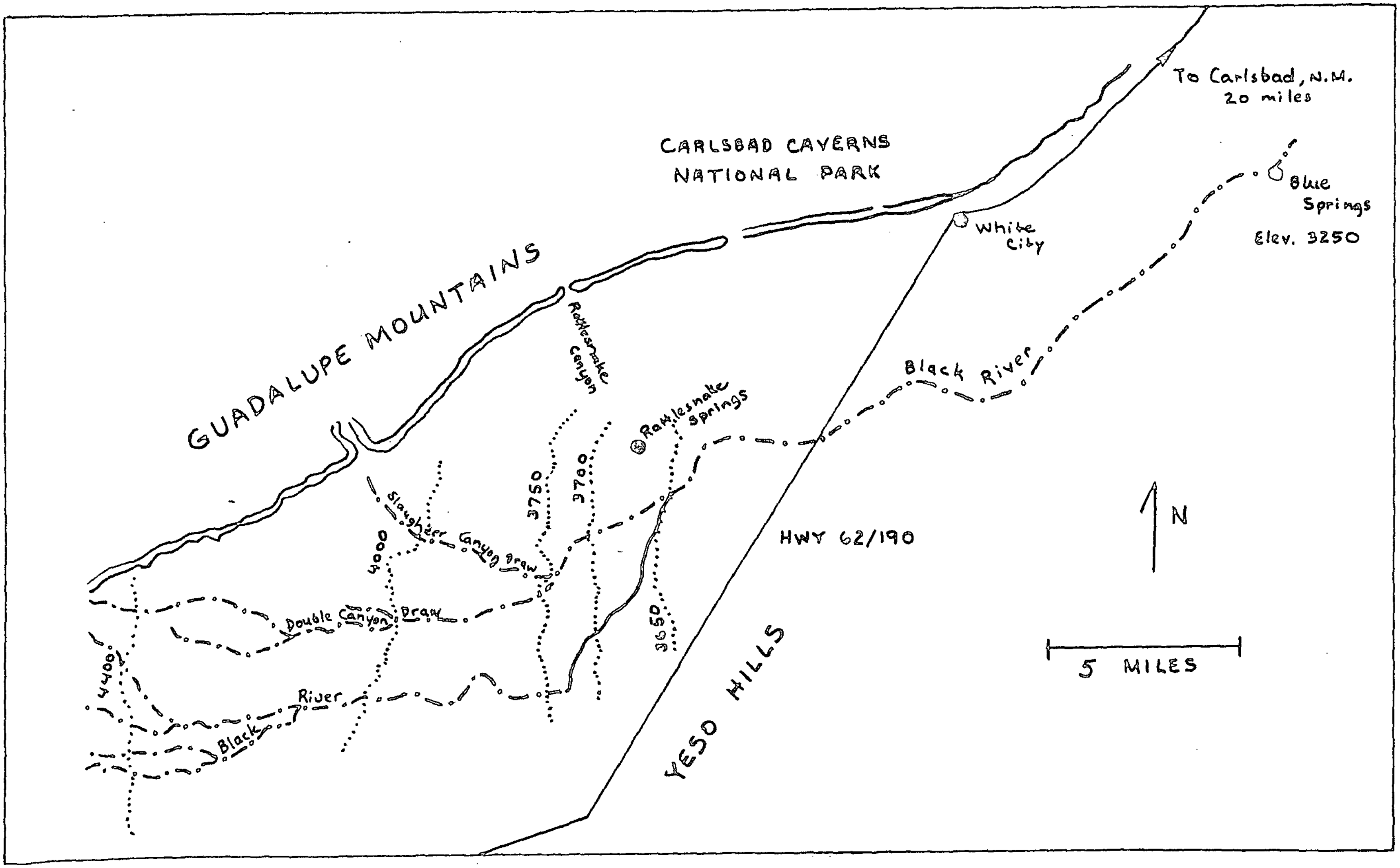
Important geologic features of the upper Black River Valley and the adjacent Guadalupe Mountains are shown in Figure 2. The Guadalupe Mountains in this area, known as the reef escarpment, are the remains of what once was the Delaware Basin (King 1948). This basin is one of the largest oil producing areas of the world. Carlsbad Caverns National Park lies on top of what remains of the reef at a distance of 5.5 miles north of Rattlesnake Springs.

The Black River Valley itself is underlain by a series of geologic formations including, in order, the alluvium, the Castile Formation, the Bell Canyon Formation, and the Morrow Formation.

The uppermost layer in the Black River Valley is the deposited alluvium, quaternary in age and produced by weathering and deposition of materials from the Guadalupe Mountains. This alluvium layer ranges in thickness from shallow near the reef escarpment to 100-350 feet deep near the Black River. It is composed of reworked gypsum, conglomerate, boulders, gravel, sand, silt, and clay (King 1952). The conglomerate is composed of limestone boulders and pebbles cemented by calcium carbonate, forming a dense rock. Fracturing and slumping occurs commonly in this material. The alluvial fans near the canyon mouths tend to be poorly sorted sand and gravel. Clays become more dominant nearer the Black River Valley.

The Castile Formation underlies the alluvium in the upper Black River Valley. When originally deposited, this formation was mostly anhydrite. Groundwaters have eroded and altered the anhydrite to gypsum and in the process have created many sink holes and channels. These have filled with alluvium materials such as sand, silt and clay to form stringers. This weathered formation is relatively thin in depth in the upper Black River Valley (Hale 1955). It extends to the southeast where it is known as the Yeso Hills (Durham et al. 1972) and to the north where it is known as the Gypsum Plains (King 1948). The Gypsum Plain is a karst formation containing sink holes, troughs, breccia, sinking streams, and gypsum caves (Hill 1987).

Figure 1. Topographical Features of the Upper Black River Valley, New Mexico.



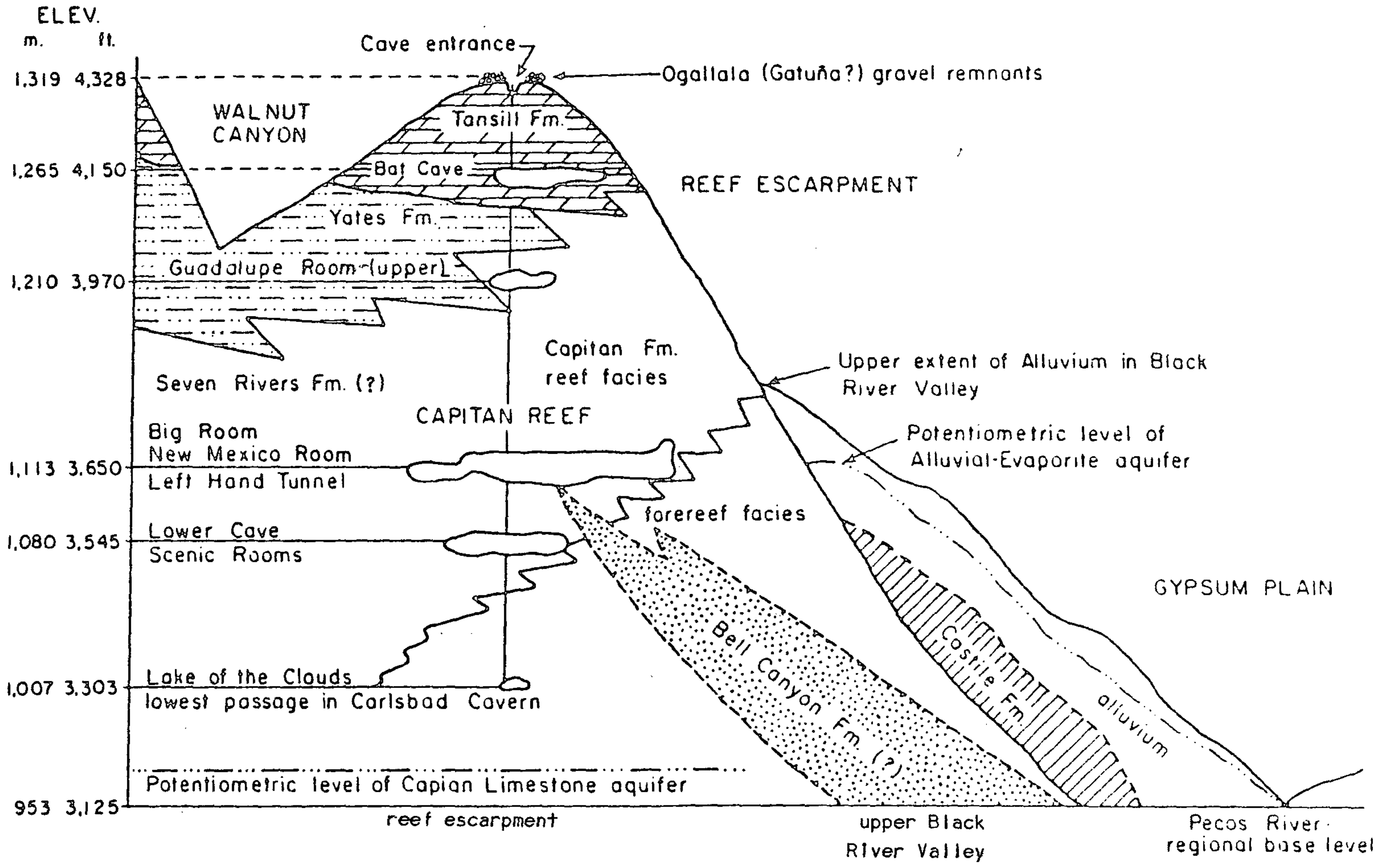


Figure 2. **Geologic Cross-Section for the Upper Black River Valley and Adjacent Guadalupe Mountains** (Adapted from Hill 1987).

The Bell Canyon Formation, an oil producing formation, underlies the Castile Formation in the upper Black River Valley. The Bell Canyon Formation consists of sandstone and limestone members (King 1948; Hill 1987). This formation was tilted a few degrees to the northeast when the Guadalupe Mountains uplifted in the geologic past, resulting in the migration of oil and gas into the Castile Formation through permeable areas such as joints. These hydrocarbons resulted in the formation of hydrogen sulfide and carbon dioxide gases in this formation, leading to sulfuric acid and its reaction with limestone to form large cave voids, including Carlsbad Caverns (Hill 1987). Boreholes drilled into the Castile Formation have shown up to 55% carbon dioxide and 28% hydrogen sulfide gas compositions (Hill 1987).

The reef escarpment is underlain by the Capitan Limestone Formation, which interfingers with the Bell Canyon Formation in the upper Black River Valley (Hendrickson 1952). This will be discussed later as it is one of the two water-bearing formations in this area (the upper Black River Valley alluvium being the second).

The Morrow Formation underlies the Bell Canyon Formation at a depth of approximately 7000 feet below the upper Black River Valley. The Morrow formation is the source of natural gas in the valley and the site of reinjected natural gas storage.

Hydrology of the Upper Black River Valley

Climate in the upper Black River Valley is semiarid with an average annual rainfall of 10-14 inches, concentrated in the summer (May-October) as storm events. The area is noted for a large year-to-year variation in rainfall. For example, the 1986-1987 season was a record wet year with approximately 30 inches of rainfall. Local rainfall in the valley and the adjacent Guadalupe Mountains is the main source of water for this area. Surface water is limited, being found only in a short section of the Black River near Rattlesnake Springs due to a series of small dams and groundwater discharge in this area. Most water use in the valley is dependent on groundwater.

Carlsbad Caverns National Park was the first significant user of groundwater in the upper Black River Valley with water rights dating to the 1880's. Water reportedly was first used in this valley for irrigation in 1946 followed by installation of numerous irrigation wells in the early 1950's. By 1952, 670 acres were being irrigated with groundwater (Hale 1955). Concern for possible effects of groundwater withdrawal for irrigation on the water supply at Rattlesnake Springs prompted an indepth investigation in 1952 on water use in the upper Black River Valley by the USGS, the New Mexico State Engineer's Office, and the NPS. The Hale Report (1955) resulted from these investigations. State control of groundwater use in the upper Black River Valley was established when the Carlsbad Groundwater Basin was created by the New Mexico State Engineer's Office in 1952. Concern over water use in the valley culminated in a court case in 1960 which apportioned water use in the valley (U.S. versus Ballard et al., No. 4194 in U.S. District Court, 1960).

There are three water-bearing geologic formations in the upper Black River Valley: the valley alluvium; the Capitan and Carlsbad limestones; and the Castile Formation. The valley alluvium and the Capitan Limestone have been designated as the Cenozoic Alluvium Aquifer and the Capitan Aquifer, respectively, by the New Mexico State Engineers Office (Richey et al. 1985).

The principal water-bearing formation in the upper Black River Valley is the alluvium. The actual flood plain of the Black River is only a few hundred yards wide, but is bordered by coalescing alluvial fans to the north and west which makes the alluvium 3 to 4 miles wide in the upper Black River Valley.

Water recharge to the alluvium is derived principally from infiltration of floodwaters in the larger canyons , e.g. Slaughter and Rattlesnake Canyons, heading in the Guadalupe Mountains, shown in Figure 1 (Hendrickson 1952; Hale 1955). Smaller amounts of water may be contributed from direct precipitation on the alluvium, from the gypsum beds (Castile Formation) to the north and south of Rattlesnake Springs, and from perched water-bearing beds in the Capitan and Carlsbad Limestones. These latter sources will be discussed later.

The upper Black River Valley alluvium consists of unconsolidated to consolidated beds of boulders, cobbles, gravel, sand, silt, and clay eroded from the nearby Guadalupe Mountains. Near the canyon mouths this alluvium is unconsolidated as coalesced alluvial fans. Nearer the Black River it is composed of reworked gypsum and consolidated limestone conglomerate. Some of the alluvium fills sinkholes developed in the underlying gypsum beds of the Castile Formation. Alluvium ranges in thickness from thin in the canyons and near the Guadalupe Mountains to depths of 90-350 feet near the Black River.

While the conglomerates constitute only a small part of the alluvium, the largest yields of groundwater are obtained from this material (Hale 1955). This conglomerate is composed of limestone pebbles and boulders cemented by calcium carbonate to form a dense, highly fractured rock with numerous voids and solution channels. The conglomerates occur most commonly as fill in buried channels cut into the underlying gypsum or older alluvium. Several cemented gravel beds occur in the upper Black River Valley which are separated by clay. These appear to act as independent aquifers, with limited hydraulic connections (Hale 1955).

Well logs for wells near Rattlesnake Springs show alluvium 100-200 feet thick. These well logs document the presence in the alluvium of coarse sand and gravel with high hydraulic conductivity (termed "stringers"). Also, numerous voids or small caverns have been encountered during well drilling into the alluvium. Groundwater flows through this alluvium primarily through stringers of conglomerate or through well defined solution channels in the conglomerate (Hale 1955). Well yields are too low for irrigation use where the conglomerate is thin, nonexistent, or without fractures.

Groundwater flow through the alluvium in the upper Black River Valley is from southwest to northeast, heading in the Guadalupe Mountains and discharging partly at Rattlesnake Springs and partly at Blue Springs (see Figure 1). Groundwater occurs under both unconfined and confined (artesian) conditions. Artesian conditions are localized, caused by an alluvium overburden of low permeability silts and clays.

Depth to the water-bearing layer in the vicinity of Rattlesnake Springs varies from 150 to 350 feet, with a static water level in wells of approximately 90-100 feet due to artesian conditions. The unconsolidated alluvium has a reported coefficient of storage of 0.2 and a coefficient of transmissibility of 25,000-60,000 gallons per day per foot (Hale 1955; Sprester and Uribe 1982). The upper Black River Valley alluvium yields large volumes of water to wells or springs. Irrigation wells near Rattlesnake Springs produce 650-1300 gallons per minute flow with minor drawdowns of 10-20 feet after 9 hours of pumping (Hale 1955; Sprester and Uribe 1982). All these high producing wells are finished in the alluvium conglomerate layer.

Groundwater discharges at Rattlesnake Springs from a conglomerate through overlying sand and gravel. In the area around the Springs in Neuro Canyon Draw, the conglomerate is overlain by silt and clay, resulting in slight artesian pressure at Rattlesnake Springs. Flow at Rattlesnake Springs varies seasonally and from year-to-year, ranging from 1.7 to 7 cubic feet per second (cfs), usually in the range 4-5 cfs. Flow is highest in January and lowest in August, the lowest flow coinciding with maximum irrigation water withdrawal in late summer.

There exist two additional water-bearing formations in the upper Black River Valley that could contribute water to the alluvium aquifer. The first is the Capitan limestone which underlies the reef escarpment and which interfingers with the Castile formation at the northern edge of the upper Black River Valley.

The zone of saturation in the Capitan limestone underlying the reef escarpment (shown in Figure 2) is at 1025 feet below the mouth of Carlsbad Caverns (unsounded pool) and at an altitude of 3325 feet. This water level is approximately 300 feet below the alluvium surface in the upper Black River Valley 1.5 miles south of the Caverns. Groundwater thus does not move south to the alluvium due to its lower elevation. It is possible that groundwater from the alluvium moves northward into the Capitan limestone, however, sandstone barriers exist that would limit this. Some perched aquifers in the Capitan limestone could contribute a small amount of recharge to the alluvium. This water would likely pick up significant chloride content from the intervening sandstone of the Guadalupe series. Since the chloride content of groundwater in the upper Black River Valley is low, contribution of water from perched aquifers in the Capitan limestone to groundwater in the alluvium appears minimal (Hale 1955).

The second source of additional recharge to the upper Black River Valley alluvium is the Castile Formation or gypsum beds. This appears to be a more significant source of water to the alluvium than the Carlsbad limestone. Stock wells finished in the gypsum beds north and east of Rattlesnake Springs where the alluvium is thin yield limited amounts of water. Groundwater originating in the gypsum beds has a high mineral and sulfate content compared to the alluvium groundwater.

The mineral content of groundwaters in the upper Black River Valley vary significantly, particularly in calcium and sulfate. The best quality water, containing less than 500 ppm sulfate, occurs to the west of Rattlesnake Springs, shown in Figure 3. Sulfate content of groundwater increases north and south of Rattlesnake Springs where recharge may occur from the gypsum beds or where groundwater flows through subsurface gypsum. The presence of low sulfate groundwater in sufficient quantity for use appears to be confined principally to a narrow strip of the upper Black River Valley running southwest to northeast from Slaughter Canyon to Rattlesnake Springs.

Reported groundwater quality for wells shown in Figure 3 agree with the generalized sulfate content contour lines also shown in Figure 3. Mineral content of groundwater at Rattlesnake Springs is low for the area, with an average bicarbonate content of 290 mg/L, a sulfate content of 110-120 mg/L, and a chloride content of 6 mg/L. Similar or lower values are observed for the Central Farm-West well, the Smart house well, and the Colwell well. There is some increase in mineral and sulfate content of groundwater in going towards Rattlesnake Springs from nearby, downgradient wells.

Higher mineral and sulfate content are observed in water from wells located east of the above wells. The Central Farm well and the two Ballard wells are reported to have approximately 600 mg/L sulfate content. Water from these wells either is partly derived from the Castile Formation (gypsum beds) or is alluvium groundwater that has traveled through subsurface gypsum deposits. It should be noted that the sulfate gradients in groundwater shown in Figure 3 are not fixed, rather, can vary seasonally or from year-to-year with varying recharge to the alluvium and the gypsum beds.

Groundwater flow in the upper Black River Valley in the vicinity of Rattlesnake Springs appears to be complex. Groundwater flows through solution channels and voids in the subsurface conglomerate and several more or less isolated aquifers may occur, separated by clay and silt barriers.

The Rattlesnake Springs aquifer appears to be tapped by at least 3 other wells. Reported hydraulic connections of nearby wells to Rattlesnake Springs are listed in Table 1 and their location is shown in Figure 4. These hydraulic connections were determined by observing diminished flows at Rattlesnake Springs when the nearby wells were being used for irrigation (Hale 1955). Hydraulic connection cannot be inferred simply by nearby location of a well, due to the existence of solution channels, stringers, caverns or voids, and the presence of silt and clay barriers in the alluvium.

The CARC, Central Farm-West, and the Smart house wells tap the same aquifer and are hydraulically connected to Rattlesnake Springs. No information could be found for the Central Farm well. The two Ballard wells, the site of current natural gas contamination, are only partly connected to Rattlesnake Springs, most of the flow from these passing south of the

Figure 3. **Major Geologic Features and Sulfate Content of Groundwaters in the Upper Black River Valley** (modified from Hale 1955).

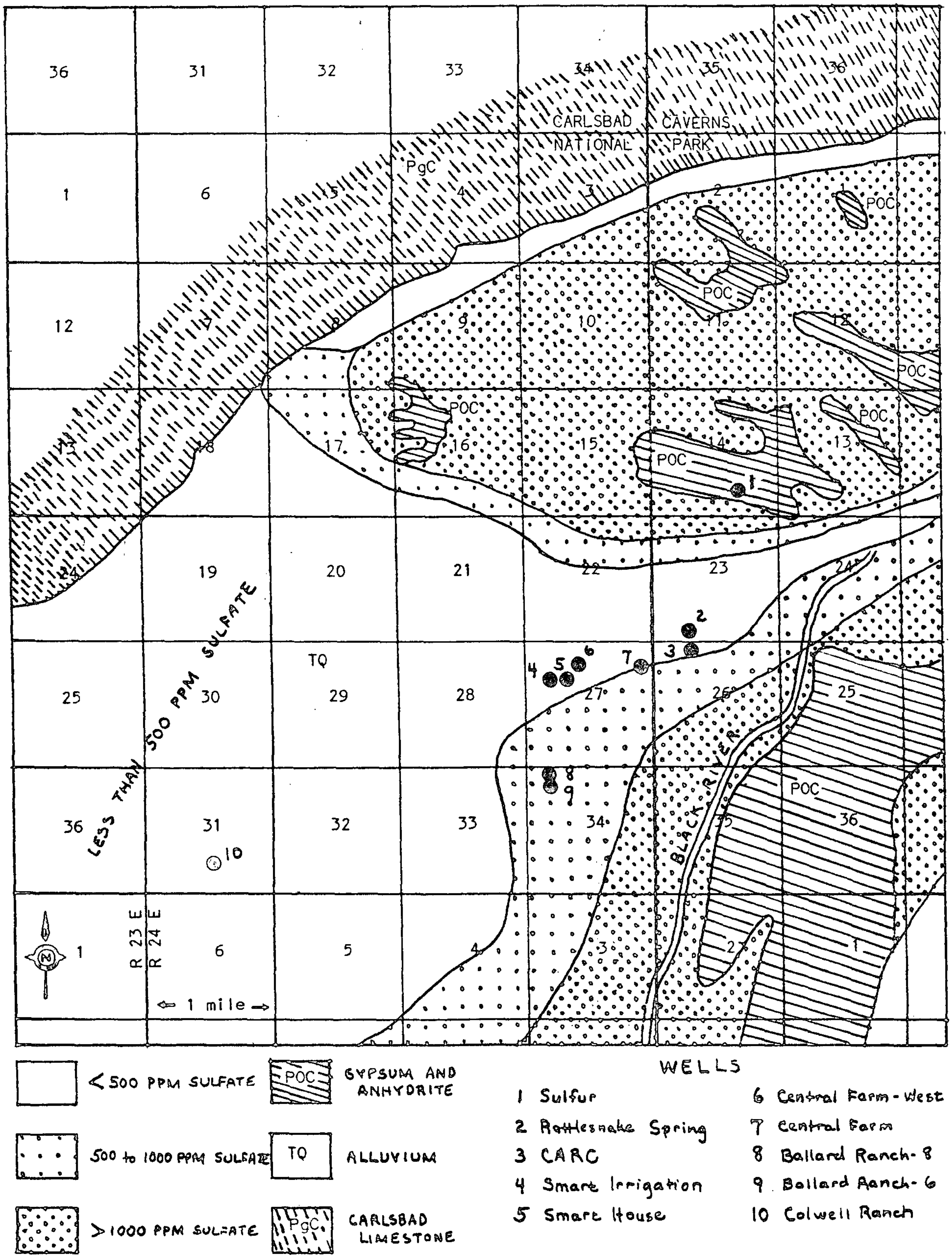


TABLE 1 . **Reported Hydraulic Connections of Nearby Wells to Rattlesnake Springs*.**

Well	**Hydraulic Connection to Rattlesnake Springs**			
	Connected	Partly Connected		Not Connected
CARC	+			
Central Farm	?	?		?
Central Farm - West	+			
Smart House	+			
Smart Irrigation		+	or	+
Ballard - 8		+		
Ballard - 6		+		
Sulfur				+

---

* based on information in Hale (1955) and the court case: **U.S. versus Ballard et al.**, No. 4194 in U.S. District Court (1960).

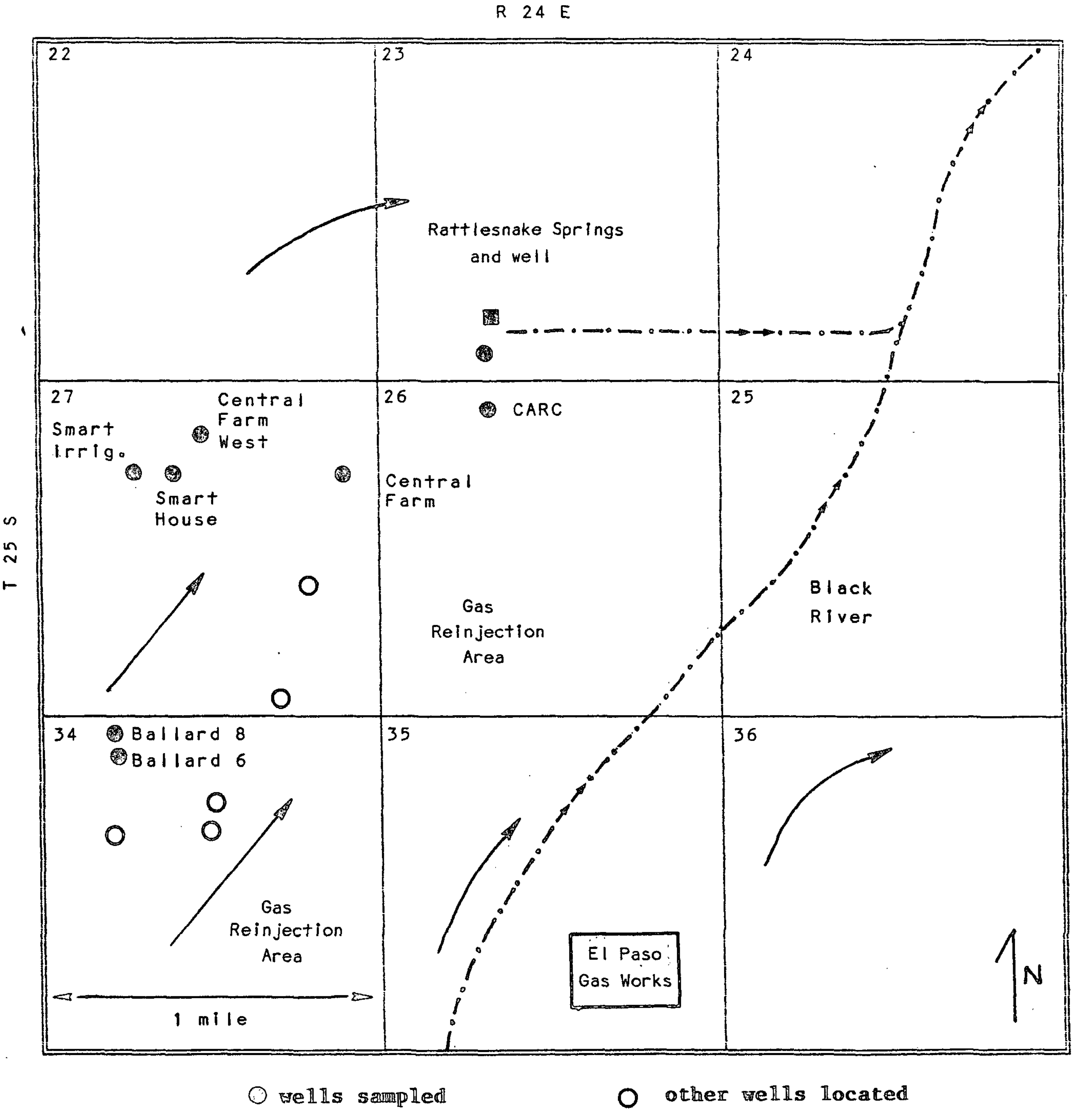


Figure 4. Location of Wells in the Vicinity of Rattlesnake Springs and Generalized Groundwater Flow in the Area.

Springs. These wells could contribute a variable amount of flow to the Springs, dependent on variable seasonal groundwater flows in the area. The Sulfur Exploration well, located north of the Springs, is not connected.

The Smart irrigation well appears to be only marginally connected to Rattlesnake Springs, or not at all, with groundwater from this well passing northwest of Rattlesnake Springs. One explanation for this is the existence of a groundwater barrier between the Smart house and irrigation wells, shown diagramatically in Figure 5. Static water levels in these two wells, located within 100 yards of each other, differ by approximately 10 feet. It may be that this barrier is not complete, and groundwter may move between these wells and hence enter the flowpath to Rattlesnake Springs at certain hydraulic conditions.

Generalized groundwater flow towards Rattlesnake Springs is shown in Figure 4. Lower elevations to the southeast of Rattlesnake Springs cause groundwater found here to flow away from the Springs. Groundwater flowing out of the perched aquifers in the Capitan limestone north of Rattlesnake Springs appears to flow eastward, not entering the Springs aquifer. Water from the Capitan limestone would be high in chloride due to passage through sandstone, and the low chloride content of groundwater at Rattlesnake Springs indicates that recharge from the Capitan limestone is not significant. The main source of groundwater to Rattlesnake Springs comes from the alluvium to the west and southwest. Groundwater traveling only through the alluvium would have lower sulfate content. Water originating in the gypsum beds or passing through subsurface gypsum deposits would have a higher sulfate content. Groundwater at Rattlesnake Springs probably represents a mixture of these two types of groundwater. The relative contribution of these two sources would determine the mineral and sulfate content of groundwater at Rattlesnake Springs.

Groundwater quality problems reported to date in the upper Black River Valley include natural high mineral content, principally hardness and sulfate; impacts of natural gas leakage from gas injection/withdrawal wells (the main emphasis of this report, discussed later); and reported bacteriological contamination. Sprester and Uribe (1982) reported in 1981 that several wells in the Miller Farm Sprinkler well field, located one mile south and upgradient of Rattlesdnake Springs, had murky water, sulfide contamination, and bacteriological contamination. The authors of this report stated that this well contamination resulted from backsiphonage of a stock tank into the supplying well. These authors further suggested that this problem was widespread in the upper Black River Valley and was the most significant groundwater contamination problem in the area.

However, review of their data and a personal visit to the area did not support these conclusions. Coliform counts reported by Sprester and Uribe for two "contaminated" wells were 0/100 mls and 6/100 mls. These are not high values. Further, this may be the only example in the immediate vicinity of Rattlesnake Springs, as no other example could be found upon site investigation.

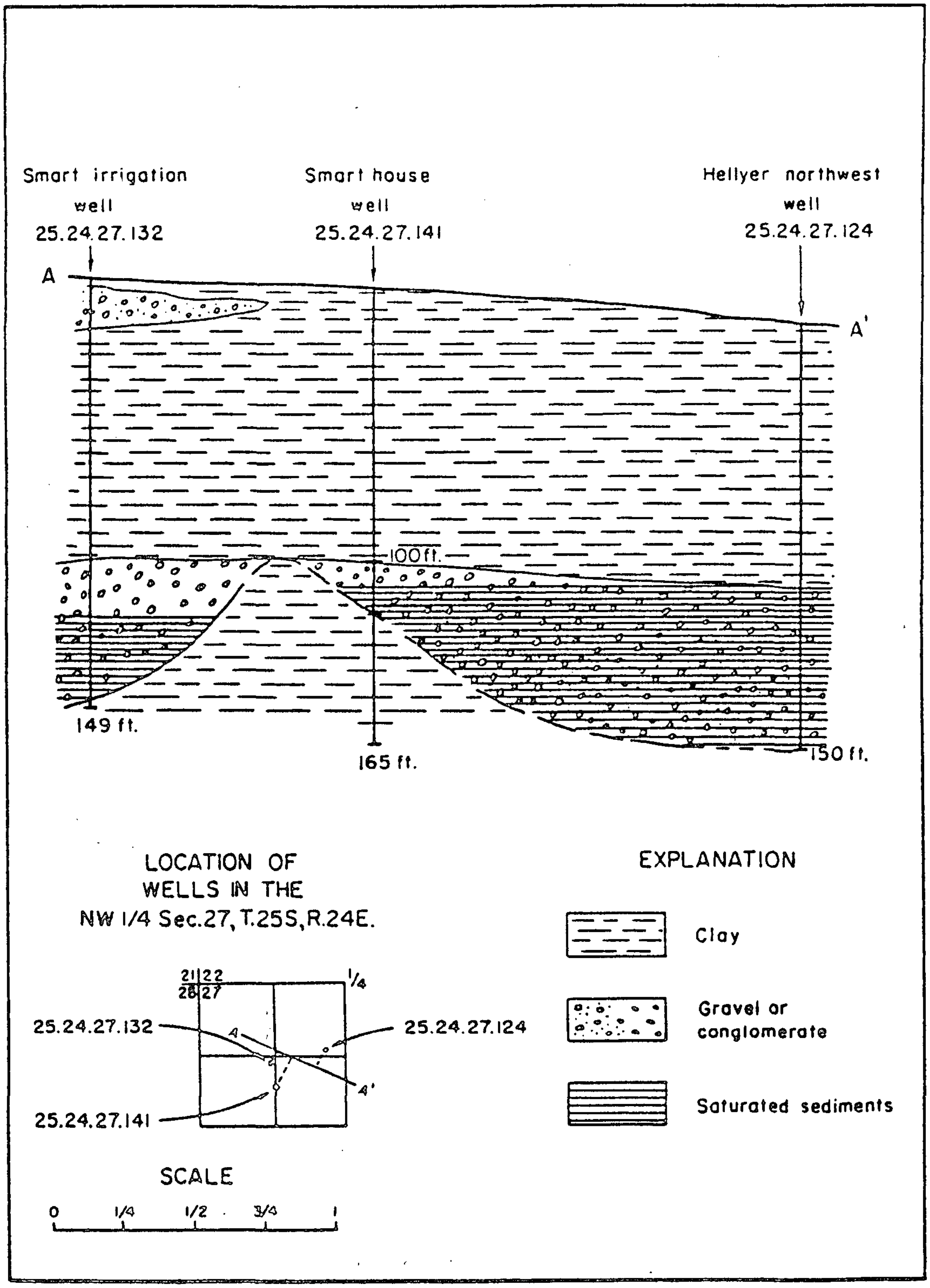


Figure 5. **Groundwater Levels and the Existence of a Subsurface Barrier Between the Smart House and Irrigation Wells** (from Hale 1955).

History of Natural Gas Reinjection by El Paso Natural Gas Company

The Washington Ranch natural gas field in the upper Black River Valley in Eddy County, New Mexico, was discovered in June, 1971, with its subsequent development by the El Paso Natural Gas (EPNG) Company. By 1981, 13 extraction wells had been finished in the Morrow Formation at depths ranging from 6795 to 6844 feet. This well field was exhausted by 1981, with cumulative gas production of 58 Bcf of natural gas.

Approval was granted in March, 1981, by the Federal Energy Regulatory Commission for the EPNG Company to use the upper Black River Valley Morrow Formation as a natural gas reinjection/storage area. Natural gas is delivered to the area via a pipeline from northern Texas and stored underground, principally in the summer, for ultimate delivery to southern California. Six of the existing gas extraction wells were modified and 17 new wells were constructed for a total of 23 gas injection/withdrawal wells. These wells are located in sections 27, 28, 33 and 34 of T 25 S and sections 3 and 4 of T 26 S (see Figures 3 and 4). Nineteen of these wells are located on the Ballard's property, essentially surrounding his irrigation and domestic supply water wells. Natural gas reinjection started sometime about 1981-1982.

Groundwater Contamination by Natural Gas in the Upper Black River Valley

Impacts on groundwater by natural gas leakage were first noticed in the area immediately adjacent to several of the gas reinjection wells shortly after gas reinjection started, sometime in 1982. Mr. Colwell, an area rancher, noted a slight lemon taste to his well water and said that oil slicks were observed in several water wells in the area. To his knowledge, only Mr. Ballard's wells had significant problems (personal communication, 8/9/88).

Mr. Ballard first noticed problems in his two wells in 1982. These included tastes and odors, discolored (black) water, and significant corrosion to well casings and pumps. Testing in 1984 revealed benzene contamination in the Ballard two wells at 9 and 19 ppb and the presence of polycyclic aromatic hydrocarbons in the well water that matched those found in the natural gas being reinjected. Mr. Ballard and other parties have filed a lawsuit against EPNG Company for this contamination which is due to be heard early in 1989. I visited the Ballard wells on 8/12/87 and observed extreme corrosion of the well casings, black-colored well water with a strong sulfide odor, black staining of bathroom fixtures and the nearby cement-lined irrigation water canals, and lack of aquatic growth or life in a stock pond supplied with contaminated well water. Mr. Ballard reported that crops would not grow with the well water and that his livestock refused to drink the water. Mr. Ballard also showed me recently a video of the removal of a severely corroded pump from one of his wells.

Possible well contamination was first noticed at the Smart house well, located 0.8 miles north of the Ballard wells and in the general flowpath of groundwater towards Rattlesnake Springs, in the summer of 1987. Mr. Smart reported debris in his domestic well and a strong sulfide/petroleum odor. He said that he suffered nausea from bathing in the water. At my site visit to the Smart house well on 8/12/87 I noticed sulfide odor in his water. Mr. Smart further reported corrosion of his well pump first noticed in the fall, 1987, and he said that this was unusual, the existing pump having been in place since 1951. There had been no previous occurrence of well corrosion problems. To my knowledge, no testing of water for contamination has been done for the Smart house well prior to this investigation.

Several of the natural gas injection/withdrawal wells located near the Ballard wells were found to be leaking shortly after installation, necessitating repairs completed in 1984. Well repair reports describing the types of repairs needed for wells No. 10 and 17 are shown in the Appendix. Well No. 10 is located approximately 1/2 mile east of the Ballard wells and well No. 17 is located approximately 3/4 mile south of the Ballard wells. Mr. David Boyer, Environmental Bureau Chief, Oil Conservation Division, State of New Mexico, told me in a personal communication (8/88) that more than two of the injection/withdrawal wells have leaked and repairs to these wells have been common. Mr. Boyer wasn't sure that all gas leakage had been stopped at present, the subject of current investigation by the Oil Conservation Division.

At issue is whether all natural gas leaks have been successfully repaired to date. A letter from Mr. David L. Siddall, attorney at law representing EPNG Company, to Mr. David Boyer of the New Mexico Oil and Gas Commission dated September 7, 1988, stated that the resevoir integrity at the Washington Ranch Gas Storage Project is maintained and tested by periodic testing casing pressures at each injection/withdrawal well (see letter in the Appendix). In a letter to Mr. Bobby Crisman, Acting Superintendent of Carlsbad Caverns National Park, dated August 1, 1988, Mr. Boyer states: "If the casing integrity [at the Washington Ranch Storage Project] is maintained and the well repairs were successful in the early 1980's, no contamination due to current practices would be expected. Current contamination would likely be a result of past practices rather than current activities" (letter shown in the Appendix).

It should be noted that groundwater sulfide contamination problems are common in this area due to the occurrence of natural gas. The observation of sulfide in groundwater alone does not prove a natural gas contamination problem from the injection/withdrawal wells. However, the observation of sulfide in accompanyment with benzene or petroleum hydrocarbons such as methane does constitute good evidence of introduced natural gas contamination.

Contaminants Observed in Groundwater near Rattlesnake Springs

Groundwater contaminants observed in Mr. Ballard's wells include sulfide, benzene, and polycyclic aromatic hydrocarbons. Sulfide is most responsible for odors, water discolorization, and corrosion.

Benzene and the polycyclic aromatic hydrocarbons exist in low concentration in natural gas and other petroleum products. These exhibit a low but significant solubility in water. Both are of a health concern as benzene and certain of the polycyclic aromatic hydrocarbons appear to be human carcinogens.

Sulfide may originate from two sources: it may be present in the natural gas itself (termed "sour" gas) or be generated in situ in groundwater through microbiological oxidation of methane in the presence of sulfate. It was first thought that the natural gas being reinjected was "sour", however, Mr. David Boyer of the Oil Conservation Division said that the natural gas being reinjected was probably scrubbed clean of sulfide. Therefore, microbiological production of sulfide during methane oxidation is now thought to be the source of this contaminant. Sulfide is generated in groundwater by microbial oxidation of methane, the microorganisms using sulfate as an electron acceptor ("oxygen source") in this oxidation:

$$CH_4 + SO_4^{--} \xrightarrow{\text{bacteria}} H_2S + CO_2 \qquad \text{(not balanced)}$$

Sulfide is thus a by-product or consequence of methane contamination.

Sulfide is corrosive to iron and steel, producing the brown-black ferric sulfide precipitate. Sulfide contamination leads to other water quality changes including a decrease in dissolved oxygen and a decrease in pH.

Potential Impacts on Rattlesnake Springs

Although to date no contaminants or impacts from natural gas leakage have been observed at Rattlesnake Springs, concern exists for this important water supply. As discussed previous, hydraulic connection appears to exist between Rattlesnake Springs and the downgradient contaminated wells. This hydraulic connection appears to be minimal at this time, but could be more significant in other years due to varying hydrological events, i.e. wet versus dry years or a sequence of years.

In the worst case scenario, impacts at Rattlesnake Springs would be similar to those observed at the Ballard wells: corrosion, tastes and odors, and the contamination by toxicants such as benzene and polycyclic aromatic hydrocarbons that would restrict water use for potable purposes.

Current Goals of the Colorado State University Investigation

Colorado State University (CSU) became involved in this potential groundwater contamination problem at Rattlesnake Springs in August, 1987, when D. Michael Richard visited the site at the request of the NPS. Dr. Richard made a preliminary assessment at that time that further effort should be made to evaluate potential water contamination at Rattlesnake Springs. The NPS subsequently funded CSU in July, 1988, to conduct a one year investigation of potential contamination at Rattlesnake Springs by natural gas leakage in the area. The goals of the present investigation by CSU are as follows:

1. to review existing information on the hydrology and geology of the upper Black River Valley in the vicinity of Rattlesnake Springs to better enable assessment of potential water contamination at the Springs.

2. to visit the site twice during the year to locate and sample available groundwater (existing wells) and to analyze these samples for a number of inorganic and organic parameters. These two sampling times were planned for August, 1988, and January, 1989, to coincide with the historic low and high groundwater flows at Rattlesnake Springs, respectively.

3. to assemble this information into a risk assessment of possible impacts of contamination and their probability at Rattlesnake Springs.

4. to provide the NPS with a review of possible remedial measures that could be taken to prevent or control water contamination at Rattlesnake Springs, including their feasibility and costs.

REFERENCES

Ballance, W.C. 1961. Groundwater Levels in New Mexico, 1961. New Mexico State Engineer, Santa Fe, NM.

Busch, F.E. and J.D. Hudson. 1967. Groundwater Levels in New Mexico, 1967. New Mexico State Engineer, Santa Fe, NM.

Dunham, R.J. 1972. Capitan Reef, New Mexico and Texas. Society of Economic Paleontologists and Mineralogists, Permian Basin Section, Pub. 72-14.

Hale, W.E. 1955. Groundwater Conditions in the Vicinity of Rattlesnake Springs, Eddy County, New Mexico. U.S. Geological Survey and New Mexico State Engineer, State Engineer's Office, Santa Fe, NM.

Hayes, P.T. 1958. Geology of the Carlsbad Caverns West Quandrangle, New Mexico- Texas. U.S. Geological Survey.

Hayes, P.T. 1974. Geology of the Carlsbad Caverns East Quandrangle, New Mexico. U.S. Geological Survey.

Hendrickson, G.E. and R.S. Jones. 1952. Geology and Groundwater Resources of Eddy County, New Mexico. New Mexico Bureau of Mines and Mineral Resources, Groundwater Report No. 3, pp. 1-169.

Hill, C.A. 1987. Geology of Carlsbad Cavern and Other Caves in the Guadalupe Mountains, New Mexico and Texas. New Mexico Bureau of Mines and Mineral Resources, Bulletin No. 117.

Hiss, W.L. 1980. Movement of Groundwater in Permian Guadalupian Aquifer Systems, Southeastern New Mexico and Western Texas. in: Dickerson, P.W. and J.M. Hoffer (Eds.). Trans-Pecos Region, Southeastern New Mexico and West Texas. New Mexico Geological Society 31st Field Conference, Guidebook, pp. 289-290.

King, P.B. 1942. Permian of West Texas and Southeastern New Mexico. The American Association of Petroleum Geologists, Tulsa, OK.

King, P.B. 1948. Geology of the Southern Guadalupe Mountains, Texas. U.S. Geological Survey Prof. Paper No. 215, pp. 1-183.

Newell, N.D., et al. 1953. The Permian Reef Complex of the Guadalupe Mountains Region, Texas and New Mexico. W.H. Freeman and Co., San Francisco, pp. 1-236.

Reeder, H.O. 1957. Groundwater Levels in New Mexico, 1957. New Mexico State Engineer, Technol. Rept. No. 22, Santa Fe, NM.

Richney, S.F. et al. 1985. Geohydrology of the Delaware Basin and Vicinity, Texas and New Mexico. U.S. Geological Survey Water Resources Investigations Report No. 84-4077.

References, continued.

Sares, S.W. 1984. Hydrologic and Geomorphic Development of Low Relief Evaporite Karst Drainage Basin, Southeastern New Mexico. M.S. Thesis, University of New Mexico, 123 pp.

Sprester, F.R. and O. Uribe. 1982. Water Resources Evalaution of the Washington Ranch Storage Project, Report to the Environmental Affairs Department, El Paso Natural Gas Company.

U.S. Geological Society. 1965. Mineral and Water Resources of New Mexico. New Mexico Bureau of Mines and Mineral Resources, Bulletin No. 87.

APPENDIX

1. Copies of Important Letters.
2. Natural Gas Injection/Withdrawal Well Repair Reports.

El Paso
Natural Gas Company

DAVID L. SIDDALL ATTORNEY AT LAW

O. BOX 1492
. PASO, TEXAS 79978
HONE: 915-541-2694

RECEIVED
SEP 9 1988
OIL CONSERVATION DIVISION
SANTA FE

September 7, 1988

David G. Boyer, Hydrogeologist
Environmental Bureau Chief
New Mexico Energy, Minerals
and Natural Resources Department
Oil Conservation Division
P. O. Box 2088
State Land Office Building
Santa Fe, New Mexico 87504

Re: <u>Washington Ranch - Reservoir Integrity Analysis</u>

Dear Mr. Boyer:

This letter is in response to your inquiry to Dr. Henry Van with respect to the above-referenced matter.

El Paso Natural Gas has a procedure in place to assure that we maintain reservoir integrity at the Washington Ranch Gas Storage Project. Specifically, we periodically measure tubing and casing pressures at each withdrawal/injection and monitor well. The tubing pressures indicate reservoir pressure. By monitoring casing pressure, we can detect any leakage from the production tubing to the casing as well as between the casing and the surrounding formations (either direction).

Sincerely,

David L. Siddall

DLS:170/rml

c: Dr. Henry Van

STATE OF NEW MEXICO
ENERGY, MINERALS AND NATURAL RESOURCES DEPARTMENT
OIL CONSERVATION DIVISION

GARREY CARRUTHERS
GOVERNOR

POST OFFICE BOX 2088
STATE LAND OFFICE BUILDING
SANTA FE, NEW MEXICO 87504
(505) 827-5800

August 1, 1988

Mr. Bobby L. Crisman
Acting Superintendent
Carlsbad Caverns National Park
3225 National Parks Highway
Carlsbad, New Mexico 88220

RE: Rattlesnake Springs Management Plan and Environmental Assessment

Dear Mr. Crisman:

The New Mexico Environmental Improvement Division (EID) has provided this agency with a copy of the above document, and an EID memorandum (enclosed) expressing concern regarding water quality because of natural gas production in the area.

Our Artesia district office has been queried regarding nearby operations and reports that no state or fee leases having production are located nearby. However, gas wells are located on federal leases, and our records indicate that reports of well repairs on several gas wells, including a well in Section 27 (T-25-S, R-24-E) about on mile southwest of the springs, have been filed with the Bureau of Land Management (BLM). The BLM Carlsbad office should be contacted for further information. Additionally, the EID has information on a contaminated water well further south in the NW¼ of Section 34. Dennis McQuillan, of the EID Ground Water Section in Santa Fe should be contacted for additional information. Finally, a February, 1982, El Paso Natural Gas Company report ("Water Resource Evaluation of the Washington Ranch Storage Project") documented serious bacteriological pollution of the Sprinkler Field Well (SW¼, NE¼, NW¼, Section 27) and other nearby water wells due to back siphoning from a stock pond into the well. Since the water aquifer has a high transmissivity (the well produces 1200 gpm) and has been documented by the NPS to impact discharge at the springs, such pollution can degrade the otherwise good water quality of the springs. The OCD is not aware if any remedial action was taken regarding the water well.

The natural gas fields in the area of Rattlesnake Springs have been largely played out and many nearby wells are now used to inject gas for underground storage. Since water is not injected, large amounts of liquids are not being produced with the recovered gas. Since 1969 the OCD has restricted disposal of produced water on leases in this area to one barrel per day. This plus the fact that few fluids are produced or injected from the nearby Washington Ranch Gas Storage Facility indicates that surface contamination from current oil and gas sources would be minimal. If the casing integrity is maintained as a result of the gas well repairs made in the early 1980's, no contamination due to any current practices would be expected. Although contamination that might be detected would need to be investigated by either OCD or EID, it more likely would be a result of past practices rather than current activities.

Based on information in the management plan, the springs create a unique riparian environment in addition to providing a water supply for the National Park. I hope the information in this letter will be useful to the Park Service in their preparation of the management plan for the springs and in site administration so that the unique values associated with it may be maintained. If I can provide further information to assist in your efforts, please contact me in Santa Fe at 827-5812.

Sincerely,

David G Boyer

David G. Boyer, Hydrogeologist
Environmental Bureau Chief

encl.

DGB:sl

cc: OCD - Artesia
Stuart P. Castle - EID Drinking Water
Dennis McQuillan - EID Ground Water
EID - Carlsbad
Chuck Bowman - NPS, Santa Fe
John Bridges - EPNG, Environmental Affairs

DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

SUNDRY NOTICES AND REPORTS ON WELLS

(Do not use this form for proposals to drill or to deepen or plug back to a different reservoir. Use Form 9-331-C for such proposals.)

1. oil well ☐ gas well ☒ other Storage

2. NAME OF OPERATOR
El Paso Natural Gas Co.

3. ADDRESS OF OPERATOR
Box 1492 El Paso, Texas 79978

4. LOCATION OF WELL (REPORT LOCATION CLEARLY. See space 17 below.)
AT SURFACE: 2209' FEL & 935' FNL
AT TOP PROD. INTERVAL:
AT TOTAL DEPTH:

6. IF INDIAN, ALLOTTEE OR TRIBE NAME

7. UNIT AGREEMENT NAME

8. FARM OR LEASE NAME
Washington Ranch Storage Project

9. WELL NO.
10

10. FIELD OR WILDCAT NAME
Washington Ranch

11. SEC., T., R., M., OR BLK. AND SURVEY OR AREA
Sec. 34, T-25-S, R-24-E

12. COUNTY OR PARISH Eddy
13. STATE N. Mex.

14. API NO.

15. ELEVATIONS (SHOW DF, KDB, AND WD)
GR 3696

16. CHECK APPROPRIATE BOX TO INDICATE NATURE OF NOTICE, REPORT, OR OTHER DATA

	REQUEST FOR APPROVAL TO:	SUBSEQUENT REPORT OF:
TEST WATER SHUT-OFF	☐	☐
FRACTURE TREAT	☐	☐
SHOOT OR ACIDIZE	☐	☐
REPAIR WELL	☐	☒
PULL OR ALTER CASING	☐	☐
MULTIPLE COMPLETE	☐	☐
CHANGE ZONES	☐	☐
ABANDON*	☐	☐
(other)		

(NOTE: Report results of multiple completion or zone change on Form 9-330.)

BUREAU OF LAND MANAGEMENT
RECEIVED
MAY 11 1984
DIST. 6 N.M.
New Mexico

17. DESCRIBE PROPOSED OR COMPLETED OPERATIONS (Clearly state all pertinent details, and give pertinent dates, including estimated date of starting any proposed work. If well is directionally drilled, give subsurface locations and measured and true vertical depths for all markers and zones pertinent to this work.)*

4-2 to 4-9,1984 - Pumped 11.5ppg salt water mud down 9 5/8" x 7" annulus and killed Delaware zone. Moved in and rigged up workover unit. Pulled 2 7/8" tubing and set RBP to isolate Morrow zone. Ran casing inspection logs to inspect 7" casing. Backed off 7" casing at 2308'. Found split collar at 1300'. Ran new 7" 23# N-80 casing with die nipple, screwed into existing 7" casing. Test 7" casing from 0-6009' to 1000 psi. Held O.K., test above and below 2308' to 3000 psi, held O.K. Ran 2 7/8" tubing to 5850' with retrieving tool. Shut well in. Moved workover unit. Waiting on 4 1/2" tubing and packer to complete operations.

Subsurface Safety Valve: Manu. and Type ____ Set @ ____ Ft.

18. I hereby certify that the foregoing is true and correct

SIGNED ____ TITLE Director, Reservoir Engineering Dept. DATE 4-24-84

(This space for Federal or State office use)

ACCEPTED FOR RECORD

APPROVED BY ____ TITLE ____ DATE ____
CONDITIONS OF APPROVAL, IF ANY:

MAY 14 1984

Carlsbad, NEW MEXICO

*See Instructions on Reverse Side

UNITED STATES

BLM - CA[redacted] THE INTERIOR

GEOLOGICAL SURVEY

SUNDRY NOTICES AND REPORTS ON WELLS

(Do not use this form for proposals to drill or to deepen or plug back to a different reservoir. Use Form 9-331-C for such proposals.)

1. oil well ☐ gas well ☐ other Gas Storage
2. NAME OF OPERATOR
   El Paso Natural Gas Co.
3. ADDRESS OF OPERATOR
   1800 Wilco Bldg, Midland, Tx 79701
4. LOCATION OF WELL (REPORT LOCATION CLEARLY. See space 17 below.)
   AT SURFACE: 2209' FEL & 935' FNL
   AT TOP PROD. INTERVAL:
   AT TOTAL DEPTH:

[redacted] IF I[redacted] NAME

7. UNIT AGREEMENT NAME

8. FARM OR LEASE NAME
   Washington Ranch Storage Project
9. WELL NO.
   10
10. FIELD OR WILDCAT NAME
   Washington Ranch Morrow
11. SEC., T., R., M., OR BLK. AND SURVEY OR AREA
   Sec. 34, T-25-S, R-24-E
12. COUNTY OR PARISH: Eddy
13. STATE: NM
14. API NO.

15. ELEVATIONS (SHOW DF, KDB, AND WD)
   GR 3696'

16. CHECK APPROPRIATE BOX TO INDICATE NATURE OF NOTICE, REPORT, OR OTHER DATA

	REQUEST FOR APPROVAL TO:	SUBSEQUENT REPORT OF:
TEST WATER SHUT-OFF	☐	☐
FRACTURE TREAT	☐	☐
SHOOT OR ACIDIZE	☐	☐
REPAIR WELL	☐	☒
PULL OR ALTER CASING	☐	☐
MULTIPLE COMPLETE	☐	☐
CHANGE ZONES	☐	☐
ABANDON*	☐	☐
(other)		

(NOTE: Report results of multiple completion or zone change on Form 9-330.)

RECEIVED SEP 11 1984 Carlsbad, New Mexico

17. DESCRIBE PROPOSED OR COMPLETED OPERATIONS (Clearly state all pertinent details, and give pertinent dates, including estimated date of starting any proposed work. If well is directionally drilled, give subsurface locations and measured and true vertical depths for all markers and zones pertinent to this work.)*

4-23/5-3/1984

1.) MIRU workover unit, retrieve bridge plug.
2.) Rig up wireline unit and set Baker Model FA-1 permanent packer at 6638' WLM, with blanking plug below packer.
3.) Run 4½" 11.6# K-55 tubing with Baker K-22 latch in seal assembly, circulate inhibited packer fluid, latch into packer.
4.) Nipple down BOP, Nipple up wellhead.
5.) Test tubing to 3000 psig, retrieve plug and return well to service.

Subsurface Safety Valve: Manu. and Type ______ Set @ ______ Ft.

18. I hereby certify that the foregoing is true and correct

SIGNED ______ TITLE Area Prod. Eng DATE 9-10-84

ACCEPTED FOR RECORD

(This space for Federal or State office use)

APPROVED BY GWQ TITLE ______ DATE ______

CONDITIONS OF APPROVAL, IF ANY:

SEP 12 1984

Carlsbad, NEW MEXICO

*See Instructions on Reverse Side

GEOLOGICAL SURVEY

SUNDRY NOTICES AND REPORTS ON WELLS

(Do not use this form for proposals to drill or to deepen or plug back to a different reservoir. Use Form 9-331-C for such proposals.)

1. oil well ☐ gas well ☒ other Storage
2. NAME OF OPERATOR
El Paso Natural Gas Co.
3. ADDRESS OF OPERATOR
Box 1492 El Paso, Texas 79978
4. LOCATION OF WELL (REPORT LOCATION CLEARLY. See space 17 below.)
AT SURFACE: 1045' FWL & 2363' FNL
AT TOP PROD. INTERVAL:
AT TOTAL DEPTH:

6. IF INDIAN, ALLOTTEE OR TRIBE NAME
7. UNIT AGREEMENT NAME
8. FARM OR LEASE NAME
Washington Ranch Storage Project
9. WELL NO.
17
10. FIELD OR WILDCAT NAME
Washington Ranch
11. SEC., T., R., M., OR BLK. AND SURVEY OR AREA
Sec. 34, T-25-S, R-24-E
12. COUNTY OR PARISH
Eddy
13. STATE
N. Mex.
14. API NO.
15. ELEVATIONS (SHOW DF, KDB, AND WD)
GR 3720

16. CHECK APPROPRIATE BOX TO INDICATE NATURE OF NOTICE, REPORT, OR OTHER DATA

	REQUEST FOR APPROVAL TO:	SUBSEQUENT REPORT OF:
TEST WATER SHUT-OFF	☐	☐
FRACTURE TREAT	☐	☐
SHOOT OR ACIDIZE	☐	☐
REPAIR WELL	☒	☐
PULL OR ALTER CASING	☐	☐
MULTIPLE COMPLETE	☐	☐
CHANGE ZONES	☐	☐
ABANDON*	☐	☐
(other)		

(NOTE: Report results of multiple completion or zone change on Form 9-330.)

17. DESCRIBE PROPOSED OR COMPLETED OPERATIONS (Clearly state all pertinent details, and give pertinent dates, including estimated date of starting any proposed work. If well is directionally drilled, give subsurface locations and measured and true vertical depths for all markers and zones pertinent to this work.)*

4-10-84 - Pump mud down 9 5/8" x 7" annulus to kill Delaware Zone. Move in and rig up workover unit, nipple down wellhead and nipple up BOP, pull and lay down 2 7/8" tubing. Set RBP above morrow zone in 7" casing to isolate. Run casing inspection logs. Pressure test 7" casing below damaged zone. Pull damaged 7" casing. Replace 7" casing and test. Retrieve RBP, run new tubing and production packer, circulate packer fluid, nipple down BOP, nipple up wellhead and release unit.

Subsurface Safety Valve: Manu. and Type ______ Set @ ______ Ft.

18. I hereby certify that the foregoing is true and correct

SIGNED ______ TITLE Director, Reservoir Engineering Dept. DATE 4-24-84

(This space for Federal or State office use)

APPROVED BY ______ TITLE ______ DATE ______
CONDITIONS OF APPROVAL, IF ANY:

APPROVED
MAY 14 '84
R. C. Pitschke
ENGINEER

*See Instructions on Reverse Side

DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

SUNDRY NOTICES AND REPORTS ON WELLS

(Do not use this form for proposals to drill or to deepen or plug back to a different reservoir. Use Form 9-331-C for such proposals.)

1. oil well ☐ gas well ☒ other Storage

2. NAME OF OPERATOR
El Paso Natural Gas Co.

3. ADDRESS OF OPERATOR
Box 1492 El Paso, Texas 79978

4. LOCATION OF WELL (REPORT LOCATION CLEARLY. See space 17 below.)
AT SURFACE: 1045' FWL & 2363' FNL
AT TOP PROD. INTERVAL:
AT TOTAL DEPTH:

6. IF INDIAN, ALLOTTEE OR TRIBE NAME

7. UNIT AGREEMENT NAME

8. FARM OR LEASE NAME
Washington Ranch Storage Project

9. WELL NO.
17

10. FIELD OR WILDCAT NAME
Washington Ranch

11. SEC., T., R., M., OR BLK. AND SURVEY OR AREA
Sect. 34, T-25-S, R-24-E

12. COUNTY OR PARISH
Eddy

13. STATE
N. Mex.

14. API NO.

15. ELEVATIONS (SHOW DF, KDB, AND WD)
GR 3720

16. CHECK APPROPRIATE BOX TO INDICATE NATURE OF NOTICE, REPORT, OR OTHER DATA

	REQUEST FOR APPROVAL TO:	SUBSEQUENT REPORT OF:
TEST WATER SHUT-OFF	☐	☐
FRACTURE TREAT	☐	☐
SHOOT OR ACIDIZE	☐	☐
REPAIR WELL	☐	☒
PULL OR ALTER CASING	☐	☐
MULTIPLE COMPLETE	☐	☐
CHANGE ZONES	☐	☐
ABANDON*	☐	☐
(other)		

(NOTE: Report results of multiple completion or zone change on Form 9-330.)

RECEIVED
MAY 11 1984
BUREAU OF LAND MANAGEMENT
DIST. 6
Carlsbad New Mexico

17. DESCRIBE PROPOSED OR COMPLETED OPERATIONS (Clearly state all pertinent details, and give pertinent dates, including estimated date of starting any proposed work. If well is directionally drilled, give subsurface locations and measured and true vertical depths for all markers and zones pertinent to this work.)*

4-10 to 4-17, 1984 - Move in and rig up workover unit. Pull 2 7/8" production tubing. Run RBP and set to isolate Morrow zone. Ran casing inspection log. Found 7" casing parted at 1361'. Cut off 7" casing at 1565' with inside cutter. Ran new 7" 23# K-55 casing with Bowen casing bowl, to reconnect casing. Test 7" casing from 0 - 5031' to 1000 psi, held O.K. Test above and below 1565' to 3000 psi, held O.K. Ran retrieving tool on 164 jts. 2 7/8" tubing, shut well in, rig down and release workover unit. Waiting on 4 1/2" tubing and packers to complete operations.

Subsurface Safety Valve: Manu. and Type ______ Set @ ______ Ft.

18. I hereby certify that the foregoing is true and correct

SIGNED ______ TITLE Director, Reservoir Engineering Dept. DATE 4-24-84

ACCEPTED FOR RECORD

(This space for Federal or State office use)

APPROVED BY GWJ TITLE ______ DATE ______
CONDITIONS OF APPROVAL, IF ANY:

MAY 14 1984

Carlsbad, NEW MEXICO

*See Instructions on Reverse Side

[redacted] TED STATES

THE INTERIOR

GEOLOGICAL SURVEY

SUNDRY NOTICES AND REPORTS ON WELLS

(Do not use this [illegible] deepen or plug back to a different reservoir. Use Form 9-331-C for such proposals.)

1. oil well ☐ gas well ☐ other gas Storage

2. NAME OF OPERATOR
El Paso Natural Gas Co

3. ADDRESS OF OPERATOR
1800 Wilco Bldg, Midland, Tx 79701

4. LOCATION OF WELL (REPORT LOCATION CLEARLY. See space 17 below.)
AT SURFACE: 1045' FWL & 2363' FNL
AT TOP PROD. INTERVAL:
AT TOTAL DEPTH:

5. LEASE [redacted]

6. IF IN[illegible]OTTEE OR TRIBE NAME

7. UNIT AGREEMENT NAME

8. FARM OR LEASE NAME
Washington Ranch Storage Project

9. WELL NO.
17 ✓

10. FIELD OR WILDCAT NAME
Washington Ranch Morrow

11. SEC., T., R., M., OR BLK. AND SURVEY OR AREA
Sec. 34, T-25-S, R-24-E

12. COUNTY OR PARISH: Eddy
13. STATE: NM

14. API NO.

15. ELEVATIONS (SHOW DF, KDB, AND WD)
GR 3720'

16. CHECK APPROPRIATE BOX TO INDICATE NATURE OF NOTICE, REPORT, OR OTHER DATA

	REQUEST FOR APPROVAL TO:	SUBSEQUENT REPORT OF:
TEST WATER SHUT-OFF	☐	☐
FRACTURE TREAT	☐	☐
SHOOT OR ACIDIZE	☐	☐
REPAIR WELL	☐	☒
PULL OR ALTER CASING	☐	☐
MULTIPLE COMPLETE	☐	☐
CHANGE ZONES	☐	☐
ABANDON*	☐	☐
(other)		

(NOTE: Report results of multiple completion or zone change on Form 9-330.)

17. DESCRIBE PROPOSED OR COMPLETED OPERATIONS (Clearly state all pertinent details, and give pertinent dates, including estimated date of starting any proposed work. If well is directionally drilled, give subsurface locations and measured and true vertical depths for all markers and zones pertinent to this work.)*

4-23/5-3/1984

1.) MIRU Workover unit, retrieve bridge plug.
2.) Rig up wireline unit and set Baker Model FA-1 permanent packer at 6600' WLM, with blanking plug below packer.
3.) Run 4½" 11.6# K-55 tubing with Baker K-22 latch in seal assembly, circulate inhibited packer fluid, latch into packer.
4.) Nipple down BOP, Nipple up wellhead.
5.) Test tubing to 3000 psig, retrieve plug and return well to service.

Subsurface Safety Valve: Manu. and Type ________ Set @ ________ Ft.

18. I hereby certify that the foregoing is true and correct

SIGNED David Myers TITLE Area Prod. Eng. DATE 9-10-84

(This space for Federal or State office use)

ACCEPTED FOR RECORD

APPROVED BY ________ TITLE ________ DATE ________

CONDITIONS OF APPROVAL, IF ANY:

SEP 1? 1984

Carlsbad, NEW MEXICO

*See Instructions on Reverse Side

Natural Gas Contamination at Rattlesnake Springs, Carlsbad Caverns National Park: Report of the First Field Investigation, August, 1988.

Report Number 2 of 4

by

Michael Richard, Ph.D.
Department of Environmental Health
Colorado State University

Submitted in partial fulfillment of NPS Contract No. RFQ 7029-8-0025

November 1, 1988

Natural Gas Contamination at Rattlesnake Springs, Carlsbad Caverns National Park: Report of the First Field Investigation, August, 1988.

Introduction

Carlsbad Caverns National Park (CCNP) relies on one source of potable water, Rattlesnake Springs, located approximately 8 miles south of the park in the upper Black River Valley. The National Park Service (NPS) has water rights to this water dating to the 1880's. Water use at CCNP ranges from 500,000 to 1,000,000 gallons per day to supply a peak visitor load of 10,000 visitors per day and to supply 20-30 year round residences used by NPS personnel. Water is scarce in this area and Rattlesnake Springs represents a unique and probably irreplaceable water resource.

The upper Black River Valley south and west of Rattlesnake Springs was developed in the 1970's as a natural gas field. After this resource was exhausted in 1981, this area was developed as a natural gas reinjection and storage facility, the Washington Ranch Gas Storage Project. By 1984, a total of 23 gas injection/withdrawal wells have been placed in service within two miles of Rattlesnake Springs.

Groundwater contamination appears to have occurred in several water wells near Rattlesnake Springs due to leakage of natural gas from several of the gas injection/withdrawal wells. Elevated concentrations of benzene and polycyclic aromatic hydrocarbons have been documented in the impacted wells along with sulfide contamination and accompanying odor and well corrosion.

At issue is whether these contaminants can move through groundwater to Rattlesnake Springs and impact this water source. Rattlesnake Springs lies approximately 1.25 miles north of the gas reinjection area and in the general path of groundwater flow. Groundwater contamination appears to have moved within one mile of Rattlesnake Springs. The goal of this investigation is to assess the potential for natural gas contamination at Rattlesnake Springs and to suggest appropriate remedial action(s).

Colorado State University (CSU) became involved in this potential groundwater contamination problem at Rattlesnake Springs in August, 1987, when Dr. Michael Richard visited the site at the request of the NPS. Dr. Richard made a preliminary assessment at that time that further effort should be made to evaluate potential water contamination at Rattlesnake Springs. The NPS subsequently funded CSU in July, 1988, to conduct a one year investigation of potential contamination by natural gas leakage at Rattlesnake Springs. The goals of the present investigation by CSU are as follows:

1. to review existing information on the hydrology and geology of the upper Black River Valley in the vicinity of Rattlesnake Springs to better enable assessment of potential water contamination at the Springs.

2. to visit the site twice during the year to locate and sample available groundwater (existing wells) and to analyze these samples for a number of inorganic and organic parameters. These two sampling times were planned for August, 1988, and January, 1989, to coincide with the historic low and high groundwater flows at Rattlesnake Springs, respectively.

3. to assemble this information into a risk assessment of possible impacts of contamination and their probability at Rattlesnake Springs.

4. to provide the NPS with a review of possible remedial measures that could be taken to prevent or control water contamination at Rattlesnake Springs, including their feasibility and costs.

Report Contents

This report summarizes CSU's field activities and data obtained for the first sampling trip to Rattlesnake Springs in August, 1988. A preliminary assessment of findings is also presented along with a detailing of plans for the second site visit, planned for January, 1989.

Dr. Michael Richard and Anita Boehm, graduate research assistant, visited Rattlesnake Springs August 7-13, 1988. Activities included discussions with area ranchers and NPS personnel, location and sampling of ten wells, and examination of records in local governmental offices (U.S. Bureau of Land Management, CCNP files, U.S. Geologic Survey, and the WHIPP project).

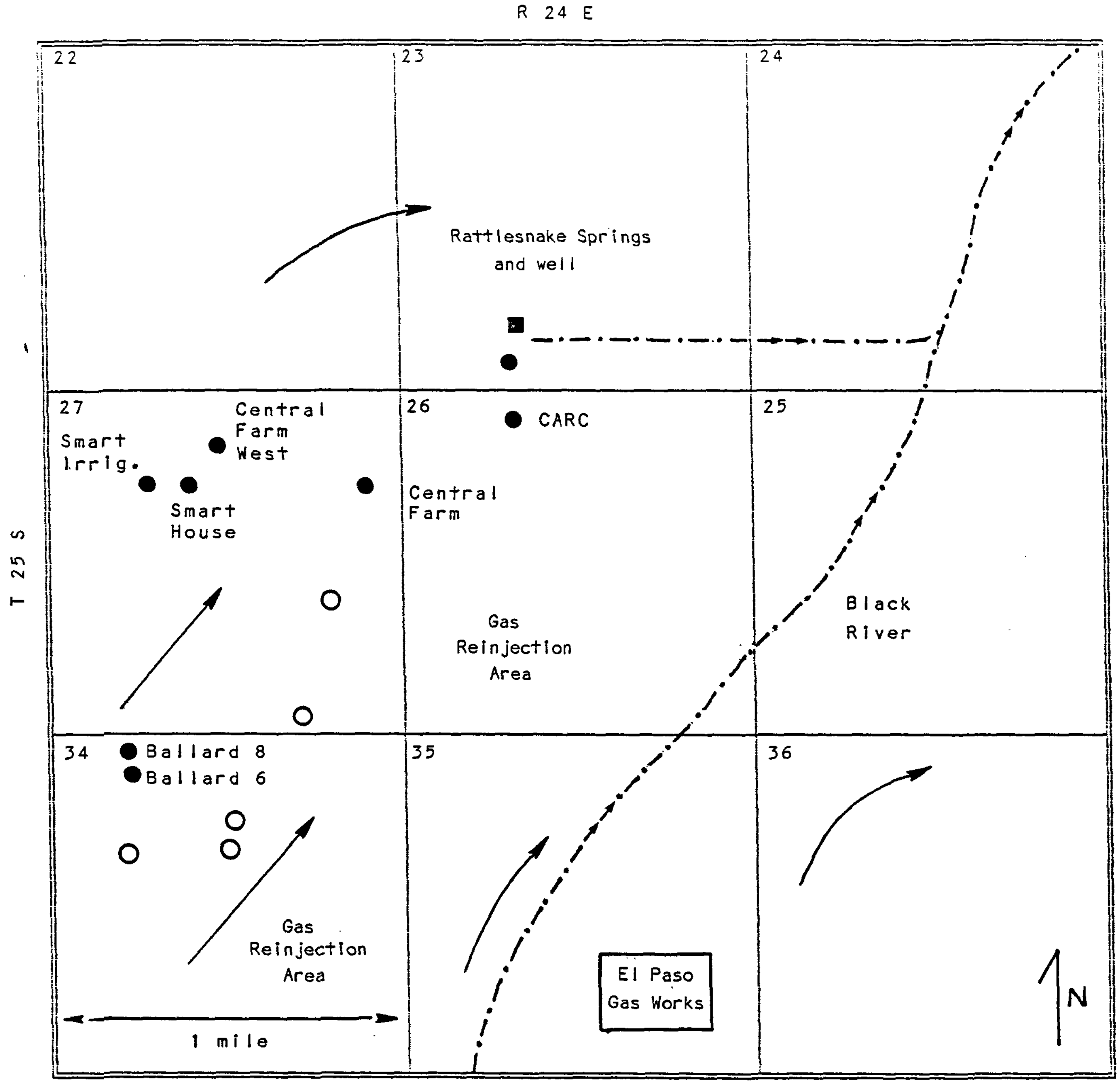
RESULTS

Location and Access to Sampling Sites

A total of 14 existing wells were located in the upper Black River Valley that could be hydraulically connected to Rattlesnake Springs. These are located principally in sections 23, 27 and 34. A subset of these consisting of 9 wells was chosen for sampling, all with owner permission. These wells are listed in Table 1 and their location relative to Rattlesnake Springs is shown in Figure 1 (the location of the Colwell and Sulfur Exploration wells is shown in Figure 2). A description of these wells obtained from well logs from the New Mexico State Engineer's Office is given in Table 2. All wells except for the Sulfur Exploration well are finished in the upper Black River Valley alluvium and could be hydraulically connected to Rattlesnake Springs. All but two of these wells were successfully sampled, shown in Table 2. The Central Farm and Central Farm - West wells were not in use, and well sealing and inoperative pumps precluded their sampling.

TABLE 1. Sampling Sites Located and Sampled.

Well Name	Sampled	Notes
Rattlesnake Springs	+	artesian; discharging continuously
CARC	+	artesian; discharging continuously
Colwell	+	used in-well pump; purged 30 min.
Ballard - 8	+	used in-well pump; purged 30 min.
Ballard - 6	+	used in-well pump; purged 30 min.
Smart House	+	used in-well pump; purged 30 min.
Smart Irrigation	+	hand bailed; no purging
Sulfur Exploration	+	artesian; purged 30 min.
Central Farm	-	sealed; no pump
Central Farm - West	-	sealed; no pump



● wells sampled ○ other wells located, not sampled

Figure 1. Location of Wells Sampled and Generalized Groundwater Flow in the Area.

Figure 2. Major Geologic Features and Sulfate Content of Groundwaters in the Upper Black River Valley (modified from Hale, 1955).

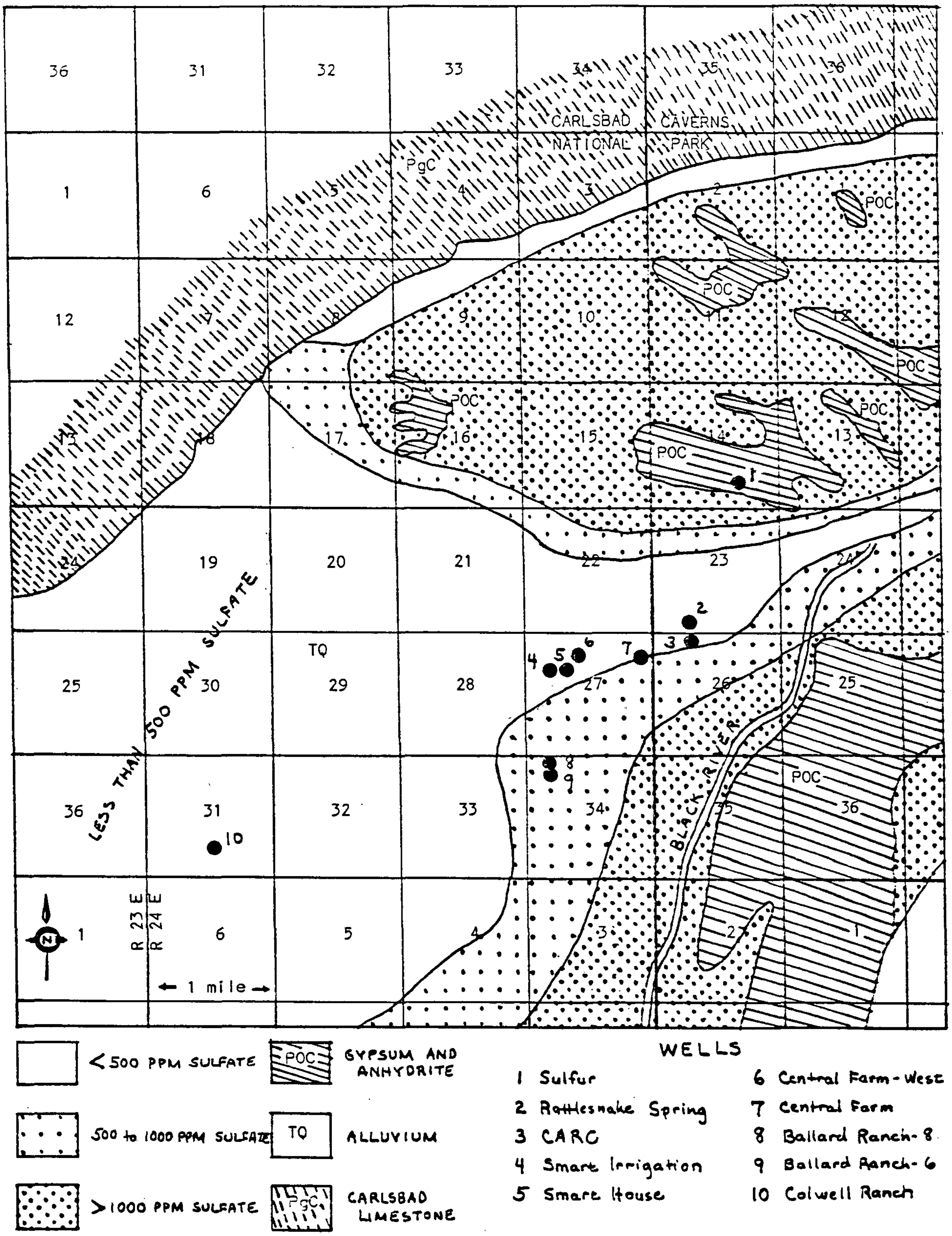


TABLE 2. Description of Wells Located for this Study.

Well Name	Well Number	Owner(s)	Date Finished	Depth feet	Diameter inches	Altitude feet	Current Use
Rattlesnake Springs	25.24.23.343	NPS	1963	118	12.75	3637	domestic - CCNP
CARC	25.24.26.121	Washington Ranch (Fish and Game)	pre 1951	170	24	3636	domestic Wash. Ranch School
Colwell	25.24.31.144	A. Colwell	pre 1951	230	7	3966	domestic + stock
Smart House	25.24.27.141	G. Smart	1952	137	10	3753	domestic
Smart Irrigation	25.24.27.132	G. Smart	1952	165	22	3749	unused - irrig.
Ballard-8	25.24.34.112a	H. Ballard	1951	165	12	3740	irrigation
Ballard-6	25.24.34.112	H. Ballard	pre 1951	97	6.5	3727	domestic + stock
Central Farm	25.24.27.224	W. Hellyer	1954	102	7	-	unused - irrig.
Central Farm - West	25.24.27.124	McClure/Hellyer (Walker/Hood)	1953	150	16	3739	unused - irrig.
Sulfur Exploration	25.24.14.___	Forest/Miller	approx. 1965	1000-1500	-	-	unused

Field Observations

On-site observations of well water contamination were made both in August, 1987, and in August, 1988, for both the Ballard wells and the Smart house well:

	Observation August, 1987	 August, 1988
Ballard wells:	strong sulfide odor black colored water well corrosion products	strong sulfide odor black colored water well corrosion products
Ballard surface pond supplied by one well:	dark in color absence of aquatic and emergent plant life	pond improved in appearance aquatic and emergent plant life evident
Smart house well:	faint sulfide odor	no sulfide odor reported well corrosion

In comparison to observations made in 1987, well water contamination in 1988 at the Ballard wells appeared on the decline. Well contamination at the Smart house well was not observed in 1988, except for the reported well corrosion.

Analytical Data

All analytical data obtained for the site visit are shown in Table 3. A listing of the analytical methods employed and the written report for the benzene/toluene/xylenes (BTX) analyses by Hagar Laboratories are shown in the Appendix. A full analysis of this data will be postponed until additional information becomes available for the January, 1989, sampling. Following is a discussion of some of the more important findings.

Except for the sulfur exploration well which draws groundwater from high gypsum strata, all groundwaters examined had similar alkalinity (bicarbonate) values. Notable differences were observed for most of the other inorganic parameters. These groundwaters can be grouped into two types, based on inorganic constituents.

Groundwater from Rattlesnake Springs and the Colwell, CARC, and Smart house wells were similar in chemistry, containing the lowest mineral content - TDS (conductivity), hardness, calcium, magnesium, sodium, sulfate and chloride. Mineral content appears to increase somewhat in going from the Smart house well to Rattlesnake Springs and the CARC well. Groundwater from the Ballard wells contained much higher mineral content, particularly calcium and sulfate, indicating subsurface travel through gypsum deposits. The Smart irrigation well water appeared to be in-between these two types of water in inorganic constituents, with a moderate increase in most dissolved materials,

Table 3. Summary of Analytical Data
August, 1988 Samples

Constituent*	RSS 8-8-88	CARC 8-8-88	Colwell 8-9-88	Smart House 8-10-88	Smart Irrigation 8-10-88	Ballard 6 8-10-88	Ballard 8 8-10-88	Sulfur Exploration 8-8-88
pH	7.15	7.36	7.14	7.16	6.90	6.79	6.85	7.45
Temperature C	26.0	25.5	23.4	23.4	26.0	24.8	22.8	24.8
Dissolved Oxygen	6.2	7.5	7.7	5.0	1.3	0.4	0.4	3.3
Conductivity	578	630	535	544	796	1363	1265	2340
TDS	338	394	320	295	520	1209	1137	3689
Alkalinity	258	251	262	252	217	256	234	60
Hardness	305	301	259	184	406	739	730	1582
Cations								
Calcium	93	94	69	26	82	250	263	544
Magnesium	18	16	21	29	49	28	18	54
Sodium	5.5	7.6	7.0	7.0	15.6	15.1	12.9	576
Anions								
Sulfate	113	169	83	65	211	989	938	2751
Bicarbonate	315	306	319	307	265	312	285	74
Chloride	4.4	5.0	6.5	9.0	55.7	11.0	9.0	43.7
H_2S	0	0	0	0	0	0.5	1.0	0
COD	3.3	3.0	1.6	5.6	5.6	6.2	5.6	16.1
Volatiles								
Benzene	<1	<1	<1	<1	<1	<1	<1	<1
Toluene	<1	<1	<1	<1	<1	<1	<1	<1
Xylenes	<1	<1	<1	<1	<1	<1	<1	<1

Sample Site

---

* all values in mg/L except for Volatiles (ug/L [ppb]) and conductivity (umho-cm, 25C).
Alkalinity and hardness are reported as mg/L $CaCO_3$.

notably chloride, compared to the nearby Rattlesnake Springs or Smart house well. A graphic comparison of the mineral (TDS) content of these waters and their sulfate and chloride content is shown in Figures 3 and 4, respectively.

All groundwater samples had low and similar COD values, with no significant differences except for a slightly higher COD value for the Sulfur Exploration well. COD values were not elevated in the two Ballard wells. No petroleum or natural gas volatiles - benzene, toluene and xylenes - were observed in any of the groundwaters, even the two Ballard wells, at a level of detection of 1 ppb. Hence, these contaminants are not significant at this time in the groundwaters examined.

Specific impacts of natural gas contamination at the Ballard wells may be the slightly lower pH values, the presence of H_2S, and the low dissolved oxygen values, shown graphically in Figures 5 and 6. The Smart irrigation well water had a lower pH and dissolved oxygen value, similar to that observed for the Ballard well waters.

Based on this preliminary information, notable impacts of natural gas contamination on groundwaters in the upper Black River Valley, observed for the two Ballard wells and possibly for the Smart irrigation well, are a lower pH value, a low dissolved oxygen concentration, and the presence of H_2S (not observed for the Smart irrigation well). All these effects on groundwater can be accounted for by the release and subsequent microbiological oxidation of methane.

Comparison of Data Obtained to Past Information

A search of the New Mexico State Engineer's records resulted in some past water quality data for the wells sampled, shown in Table 4. Current sampling results, shown in Table 3, agree well with historic water quality data for each of the sites where data is available. Rattlesnake Springs and the Colwell, CARC, and Smart house wells all appear to have the best water quality, lowest in dissolved minerals and sulfate. The Smart irrigation well has a slightly higher mineral and sulfate content than the wells above. The Ballard wells historically have had much higher mineral and sulfate values than for other wells examined in the area. No current information is available for the Central Farm and Central Farm - West wells, however, these historically have differed in water quality. The Central Farm - West well in the past had good water quality, similar to Rattlesnake Springs. The Central Farms well historically has had higher mineral and sulfate content, similar to groundwater at the Ballard wells. All sulfate values found in this study are consistent with the historic pattern of sulfate in the upper Black River Valley, shown in Figure 2.

Sulfate content of groundwater may be a good indicator of the source or travel path of groundwater in the area. Groundwater that passes through gypsum picks up significant sulfate and other dissolved minerals. The relative contribution of groundwater that has passed through gypsum areas to water at Rattlesnake Springs can be judged, at least partly, by the sulfate content of groundwater at Rattlesnake Springs. Historic sulfate values at Rattlesnake

Figure 3. Total Dissolved Solids (TDS) of Groundwaters Sampled.

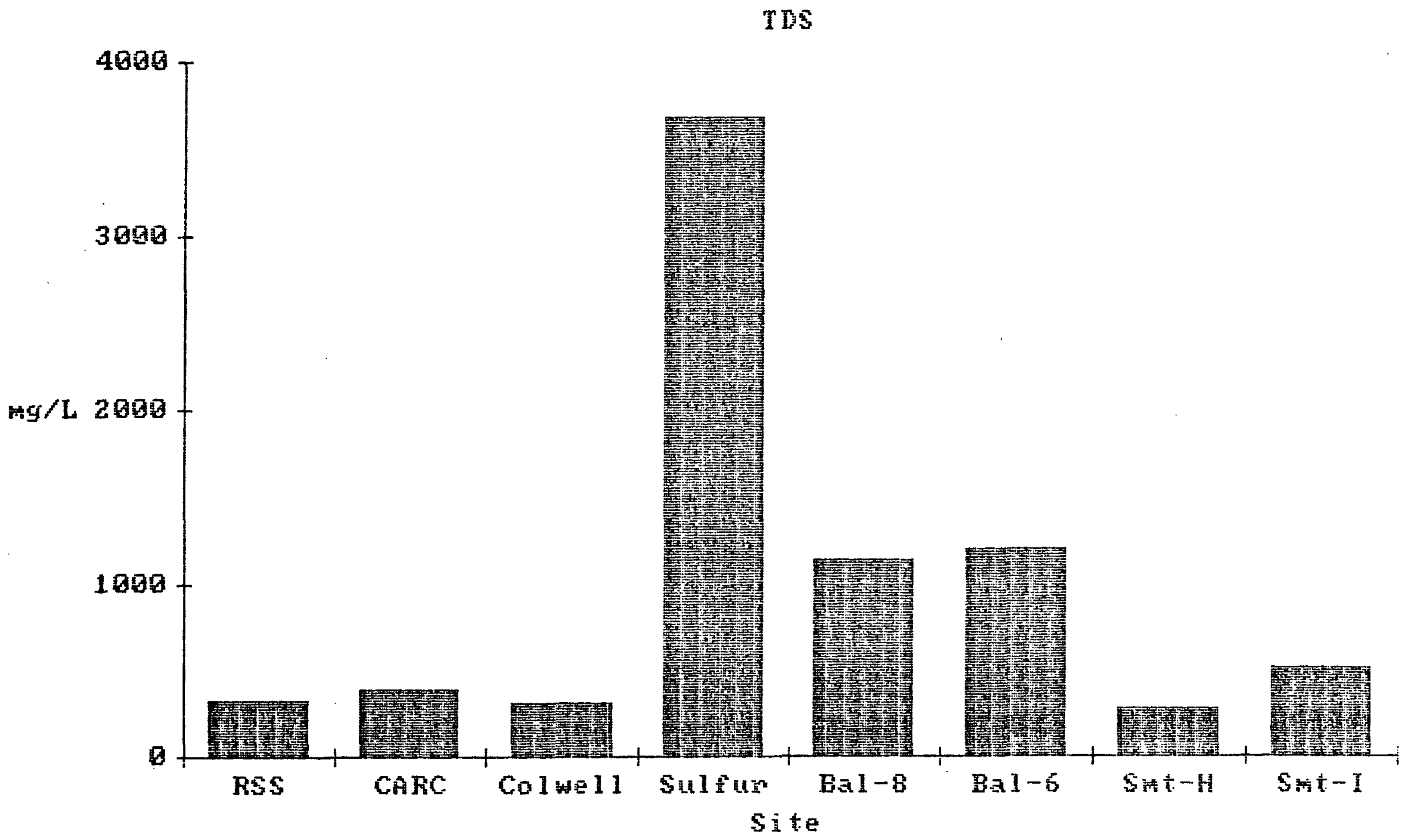


Figure 4. Sulfate and Chloride Content of Groundwaters Sampled.

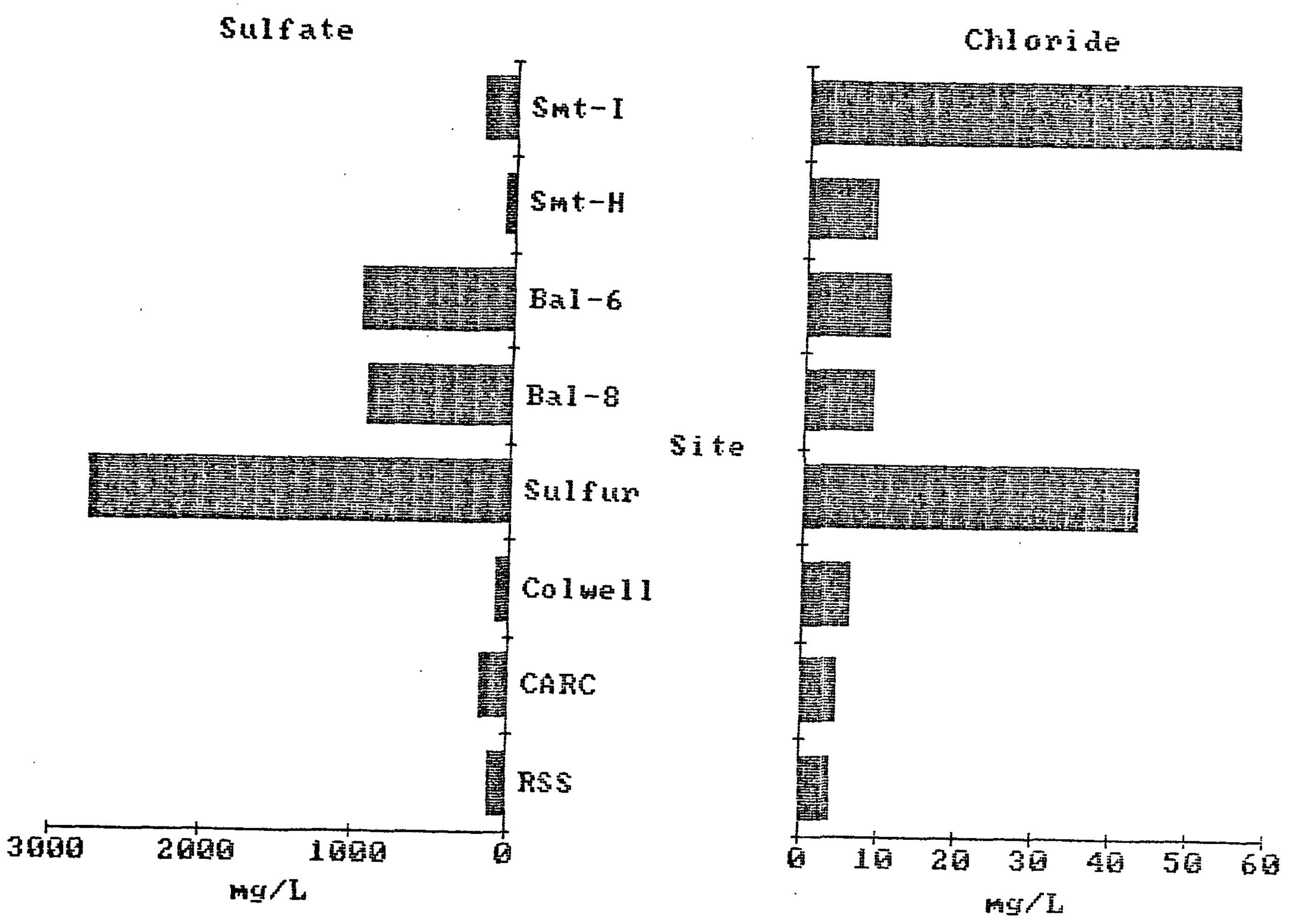


Figure 5. pH of Groundwaters Sampled.

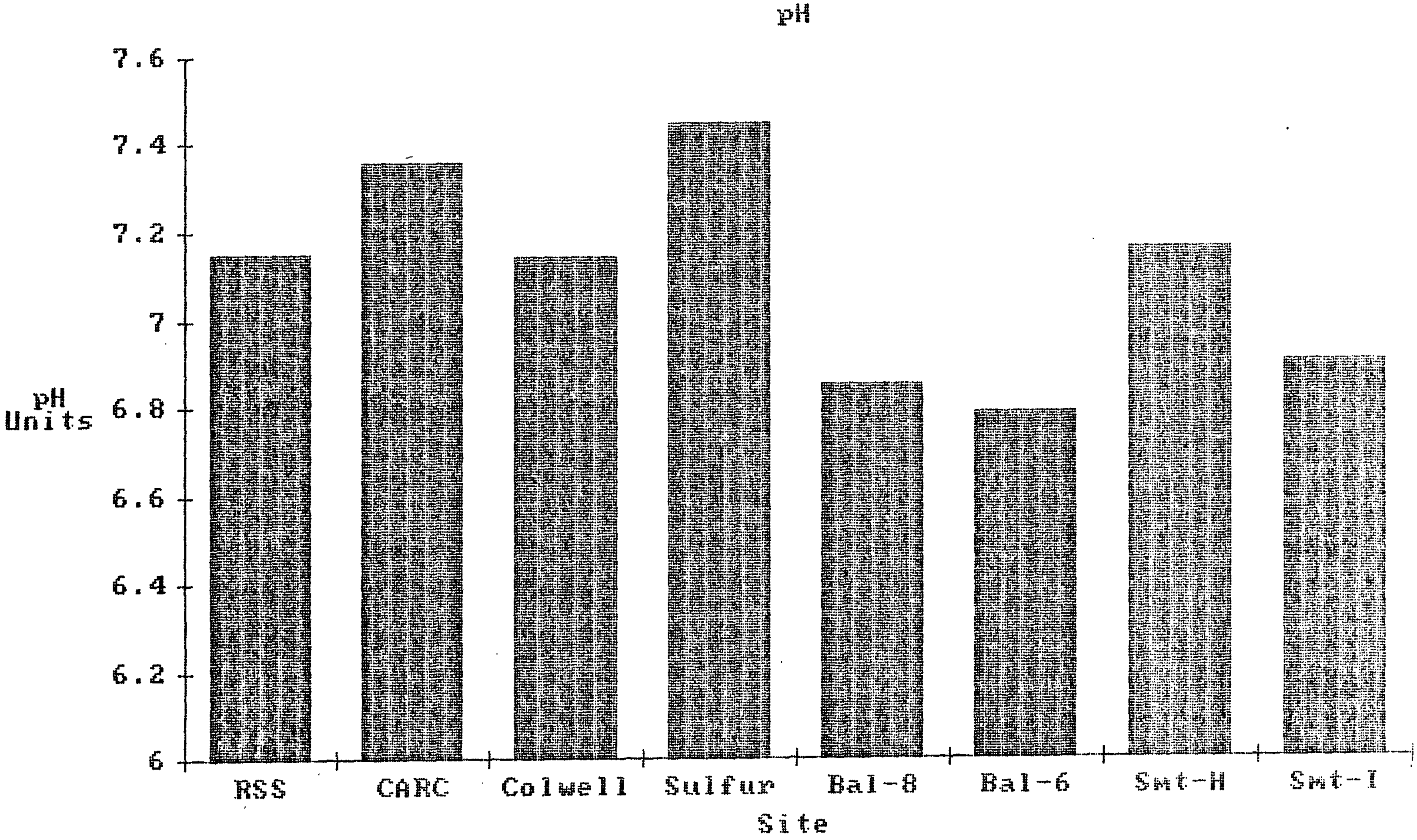


Figure 6. Dissolved Oxygen and H_2S in Groundwaters Sampled.

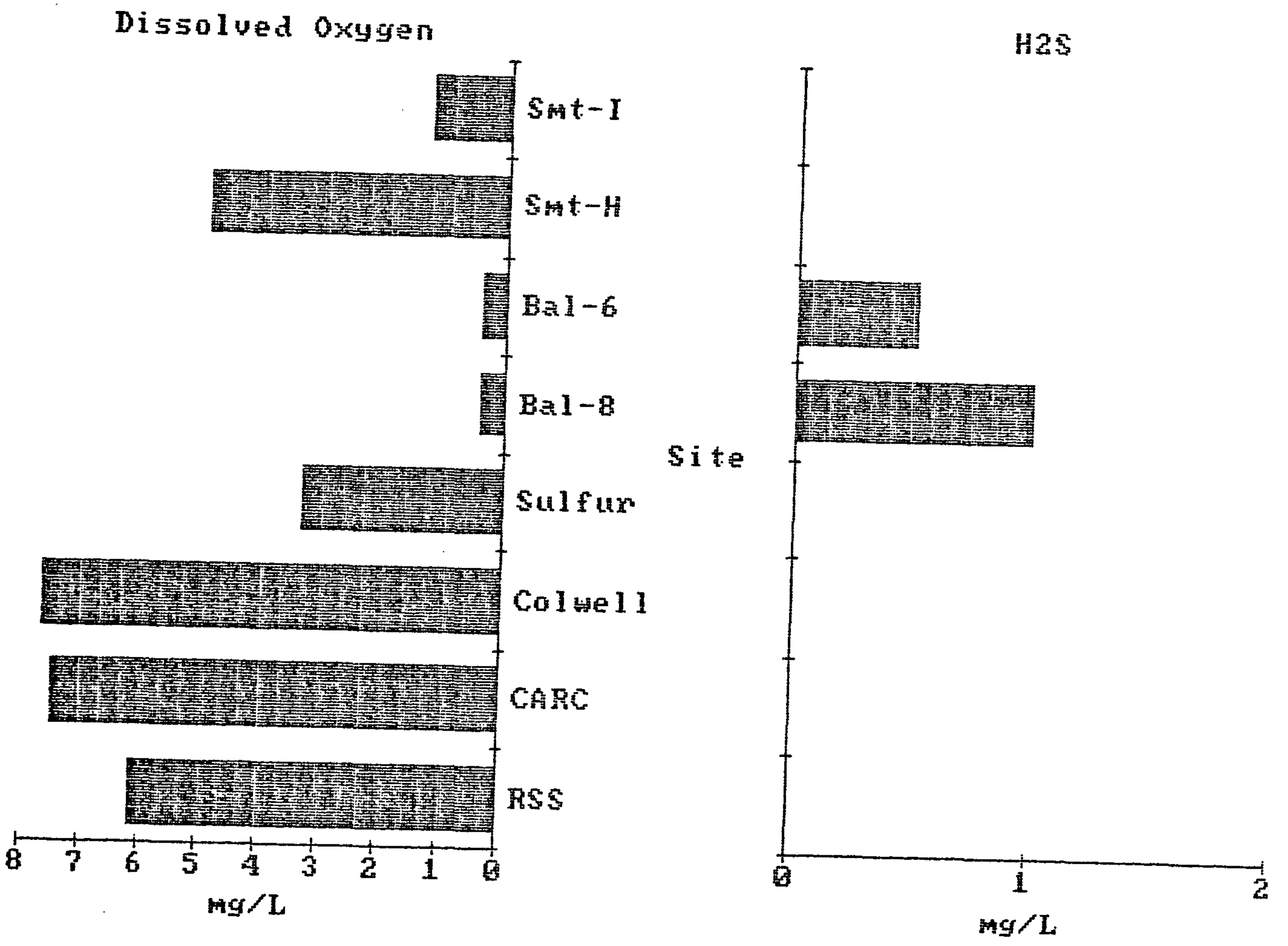


TABLE 4 . Reported Chemical Quality of Groundwaters in the Vicinity of Rattlesnake Springs.

Well	Date		Chemical Parameter, mg/L			
		Conductivity (umho/cm,25C)	Hardness	Bicarbonate	Sulfate	Chloride
Colwell	5-15-52	578	306	287	72	10
RSS	1-26-48	651	362	287	120	6
	4-6-52	673	362	283	-	6
	1-2-75	-	514	238	300	11
	5-2-86	621	350	291	111	12
CARC	10-1-52	619	333	286	105	6
Central Farm	4-6-52	1380	840	252	621	8
Central Farm - West	6-18-52	523	283	296	39	5
Smart Irrigation	5-15-52	694	351	259	144	16
Ballard - 8	4-4-52	1310	774	243	565	10
	7-15-53	1072	-	-	-	39
	8-8-85	1248	-	-	-	11

Springs have generally been in the range 110-120 mg/L, as observed for the 8-8-88 sample (see Table 3). However, higher sulfate values to 300 mg/L have been observed at Rattlesnake Springs in the past (1-2-75 in Table 4). This indicates that higher sulfate content groundwater can enter the Rattlesnake Springs aquifer at times, possibly indicating a hydraulic connection to Ballard's wells or other high sulfate groundwater in the area.

Conclusions and Preliminary Assessment

Groundwater contamination problems in the upper Black River Valley caused by leaking injection/withdrawal gas wells appear to be diminishing. This may be due to proper repair of leaking wells, completed in 1984. What is being observed may be the aftermath of a limited time natural gas leak to the upper Black River Valley alluvium aquifer. To date, no groundwater contaminants have been observed at Rattlesnake Springs. The main groundwater contamination plume may have attenuated or may have bypassed Rattlesnake Springs, probably to the south. However, this conclusion is tentative and a possible groundwater contamination problem still exists at Rattlesnake Springs if significant contamination remains in the area but not currently situated at one of the wells sampled.

The second sampling planned for January, 1989, will further evaluate these questions, dependent on access and sampling of several important wells located between Smart's house well and Rattlesnake Springs, i.e. the Central Farm and Central Farm - West wells.

Future Needs

Field support by the NPS will be needed for the planned January, 1989, sampling to the upper Black River Valley by CSU. Important to this investigation is the proper sampling of three wells located between Ballard's contaminated wells and Rattlesnake Springs: the Smart irrigation well and the two Central Farm wells. A portable submergible pump and a portable generator will be needed to properly purge and sample the Smart irrigation well. The two Central Farm wells have pumps installed that , hopefully, still work. A drive mechanism is needed to purge and sample these wells. Mr. Crisman at CCNP suggested that the NPS could supply a small tractor with an appropriate drive coupling to fit the well pumps. Hopefully, CCNP personnel can supply this needed equipment and help in getting these wells operating.

APPENDIX

1. Analytical Methods Employed.
2. Hagar Laboratories Report for BTX Analyses.

TABLE . ANALYTICAL METHODS EMPLOYED

Location	Parameter	Method
on-site	pH	Orion #231 portable pH meter
	temperature	Orion #231 portable pH meter
	conductivity	Cole Parmer #4070 conductivity meter
	alkalinity	HACH titration; potentiometric endpoint (4.3)
	Dissolved Oxygen	HACH azide modification Winkler titration
	H_2S	Gastec 211L sulfide ion detector tube
CSU laboratory	TDS	gravimetric (Std. Methods #209B)
	hardness	HACH Manver 2 CDTA titration
	Calcium	HACH Calver 2 EDTA titration
	Magnesium	by difference hardness and calcium
	Sodium	Atomic Absorption Spectroscopy
	Sulfate	HACH turbidometric barium sulfate method
	Bicarbonate	by calculation from pH and alkalinity
	Chloride	HACH mercuric nitrate titration
	COD	HACH micro dichromate acid digestion
Hagar Lab. Englewood, CO	Benzene Toluene Xylenes	EPA Method # 524.2; GC-MS

Water samples held at 4C for a maximum of 7 days without preservatives.
COD samples field acidified to pH <1 with sulfuric acid.
BTX samples collected in 40 ml headspace-free borosilicate glass vials with teflon septa and field acidified to pH <1 with sulfuric acid.

HAGER
LABORATORIES, INC.

11234 East Caley Avenue
Englewood, Colorado 80111
(303) 790-2727 (800) 282-1835
FAX # (303) 790 2756

REPORT ON SERVICE NUMBER 36608EN
October 4, 1988

Customer Project Code:

To: Mr. Michael Richard
Department of Environmental Health
Colorado State University
Ft. Collins, CO 80523

Analysis: The following samples were submitted for analysis:
Eight water samples for EPA Method 524.2 Volatile Organics.

Method: EPA Method 524.2: Volatile Organics (Water) by GC/MS.
Surrogate and internal standards are added to a 25 ml water sample. Helium is then bubbled through the water contained in a specially designed chamber. The purgeables are swept through a sorbent trap. The trap is then heated and back flushed with helium to desorb the purgeables onto a fused silica gas chromatographic column. The gas chromatograph is then temperature programmed to separate the purgeables which are detected with an electron impact quadrupole mass spectrometer.

QUALITATIVE ANALYSIS
Compounds are identified through interpretation of mass spectra by comparison of the sample mass spectrum to the mass spectrum of a standard of the suspected compound. Two criteria must be satisfied to verify the identifications: (1) elution of the sample component at the same GC relative retention time as the standard component and (2) correspondence of the sample component and standard component mass spectra.

Results: The results are found on Table 1.

Discussion: Hager Laboratories Inc. has been AIHA accredited since 1977.

Laboratory data are filed and available upon request.

If you have any questions, please call customer service.

Submitted by: Michael Aaronson
Michael Aaronson, Ph.D.
Environmental Chemistry Manager

MA/sn

TABLE 1

Sample Number	Hager Reference No.	Analysis	Concentration (ug/L)	Detection Limit (ug/L)
RSS	AA-29181-1	benzene	ND	1.
		toluene	ND	1.
		xylene	ND	1.
CARC	AA-29182-1	benzene	ND	1.
		toluene	ND	1.
		xylene	ND	1.
Colwell	AA-29183	benzene	ND	1.
		toluene	ND	1.
		xylene	ND	1.
Sulfur	AA-29184-1	benzene	ND	1.
		toluene	ND	1.
		xylene	ND	1.
Ballard-8	AA-29185	benzene	ND	1.
		toluene	ND	1.
		xylene	ND	1.
Ballard-6	AA-29186	benzene	ND	1.
		toluene	ND	1.
		xylene	ND	1.
Smart Home	AA-29187	benzene	ND	1.
		toluene	ND	1.
		xylene	ND	1.
Smart Irrigation	AA-29188	benzene	ND	1.
		toluene	ND	1.
		xylene	ND	1.

Note: ND - not detected at a detection limit of 1 ug/L.

Natural Gas Contamination at Rattlesnake Springs, Carlsbad Caverns National Park: Report of the Second Field Investigation, March, 1989.

Report Number 3 of 4

by

Michael Richard, Ph.D. and Anita Boehm
Department of Environmental Health
Colorado State University

Submitted in partial fulfillment of NPS Contract No. RFQ 7029-8-0025

May 15, 1989

Natural Gas Contamination at Rattlesnake Springs, Carlsbad Caverns National Park: Report of the Second Field Investigation, March, 1989.

Introduction

Carlsbad Caverns National Park (CCNP) relies on one source of potable water, Rattlesnake Springs, located approximately 8 miles south of the park in the upper Black River Valley. The National Park Service (NPS) has water rights to this water dating to the 1880's. Water use at CCNP ranges from 500,000 to 1,000,000 gallons per day to supply a peak visitor load of 10,000 visitors per day and to supply 20-30 year round residences used by NPS personnel. Water is scarce in this area and Rattlesnake Springs represents a unique and probably irreplaceable water resource.

The upper Black River Valley south and west of Rattlesnake Springs was developed in the 1970's as a natural gas field. After this resource was exhausted in 1981, this area was developed as a natural gas reinjection and storage facility, the Washington Ranch Gas Storage Project. By 1984, a total of 23 gas injection/withdrawal wells have been placed in service within two miles of Rattlesnake Springs.

Groundwater contamination appears to have occurred in several water wells near Rattlesnake Springs due to leakage of natural gas from several of the gas injection/withdrawal wells. Elevated concentrations of benzene and polycyclic aromatic hydrocarbons have been documented in the impacted wells along with sulfide contamination and accompanying odor and well corrosion.

At issue is whether these contaminants can move through groundwater to Rattlesnake Springs and impact this water source. Rattlesnake Springs lies approximately 1.25 miles north of the gas reinjection area and in the general path of groundwater flow. Groundwater contamination appears to have moved within one mile of Rattlesnake Springs. The goal of this investigation is to assess the potential for natural gas contamination at Rattlesnake Springs and to suggest appropriate remedial action(s).

Colorado State University (CSU) became involved in this potential groundwater contamination problem at Rattlesnake Springs in August, 1987, when Dr. Michael Richard visited the site at the request of the NPS. Dr. Richard made a preliminary assessment at that time that further effort should be made to evaluate potential water contamination at Rattlesnake Springs. The NPS subsequently funded CSU in July, 1988, to conduct a one year investigation of potential contamination by natural gas leakage at Rattlesnake Springs. The goals of the present investigation by CSU are as follows:

1. to review existing information on the hydrology and geology of the upper Black River Valley in the vicinity of Rattlesnake Springs to better enable assessment of potential water contamination at the Springs.

2. to visit the site twice during the year to locate and sample available groundwater (existing wells) and to analyze these samples for a number of inorganic and organic parameters. These two sampling times were planned for August, 1988, and January, 1989, to coincide with the historic low and high groundwater flows at Rattlesnake Springs, respectively.

3. to assemble this information into a risk assessment of possible impacts of contamination and their probability at Rattlesnake Springs.

4. to provide the NPS with a review of possible remedial measures that could be taken to prevent or control water contamination at Rattlesnake Springs, including their feasibility and costs.

Report Contents

This report summarizes CSU's field activities and data obtained for the second sampling trip to Rattlesnake Springs in March, 1989. A preliminary assessment of findings is presented. Final conclusions for this study will be given in the final project report (No. 4), to be submitted in 4 weeks.

Anita Boehm and Jane Mitchell, graduate research assistants, visited Rattlesnake Springs March 11-14, 1989. Activities included discussions with area ranchers and NPS personnel and sampling of eight wells.

RESULTS

Location and Access to Sampling Sites

A total of 14 existing wells were located in the upper Black River Valley that could be hydraulically connected to Rattlesnake Springs. These are located principally in sections 23, 27 and 34. A subset of these consisting of 9 wells was chosen for sampling, all with owner permission. These wells are listed in Table 1 and their location relative to Rattlesnake Springs is shown in Figures 1 and 2. A description of these wells obtained from well logs from the New Mexico State Engineer's Office is given in Table 2. All wells sampled are finished in the upper Black River Valley alluvium and could be hydraulically connected to Rattlesnake Springs. All but one of these wells were successfully sampled, shown in Table 1. The Central Farm well was not sampled due to an electrical outage caused by a recent natural gas fire in the vicinity. Backup sampling equipment requested of the NPS was not available to sample this well.

Field Observations

On-site observations of well water contamination were made in August, 1987; in August, 1988; and in March, 1989, for both the Ballard wells and the Smart house well:

	Observation		
	August, 1987	**August, 1988**	**March, 1989**
Ballard wells:	strong sulfide odor black colored water well corrosion products	strong sulfide odor black colored water well corrosion products	strong sulfide odor black colored water well corrosion products
Ballard surface pond supplied by one well:	dark in color absence of aquatic and emergent plant life	pond improved in appearance aquatic and emergent plant life evident	pond appeared healthy water being used for irrigation and livestock
Smart House Well:	faint sulfide odor	no sulfide odor reported well corrosion	no sulfide odor reported well corrosion

In comparison to earlier observations made in 1987 and 1988, well water contamination in 1989 at the Ballard wells appeared on the decline. Well contamination at the Smart house well were not observed in 1989, except for the reported well corrosion.

Analytical Data

All analytical data obtained for the second site visit are shown in Table 3. A listing of the analytical methods employed and the written report for the benzene/toluene/ethyl benzene/xylenes (BTEX) analyses by Hager Laboratories are shown in the Appendix. Following is a brief discussion of some of the more important findings.

All groundwaters examined had similar alkalinity (bicarbonate) values. Notable differences were observed for most of the other inorganic parameters. A graphical presentation of the results for TDS, sulfate, chloride, pH, dissolved oxygen, and hydrogen sulfide for both the August, 1988, and March, 1989, samplings is shown in Figures 3 through 7. These groundwaters can be grouped into two types, based on inorganic constituents.

RECEIVED

AUG 21 1989

OIL CONSERVATION DIV.
SANTA FE

Natural Gas Contamination at Rattlesnake Springs, Carlsbad Caverns National Park: Final Summary of the Investigation.

Report Number 4 of 4

by

Michael Richard, Ph.D. and Anita Boehm
Department of Environmental Health
Colorado State University

Submitted in fulfillment of NPS Contract No. RFQ 7029-8-0025

July 31, 1989

Natural Gas Contamination at Rattlesnake Springs, Carlsbad Caverns National Park: Final Summary of the Investigation.

Introduction

Carlsbad Caverns National Park (CCNP) relies on one source of potable water, Rattlesnake Springs, located approximately 5.5 miles south of the park in the upper Black River Valley. Water use at CCNP ranges from 500,000 to 1,000,000 gallons per day to supply a peak visitor load of 10,000 visitors per day and to supply 20-30 year round residences used by NPS personnel. Water is scarce in this area and Rattlesnake Springs represents a unique and probably irreplaceable water resource.

The upper Black River Valley is a small valley of approximately 35 miles in length bordered on the north and northeast by the Guadalupe Mountains and on the east by the Yeso Hills, shown in Figure 1. Groundwater recharge in the Valley comes from infiltration of rainfall and run-off heading in the canyons of the Guadalupe Mountains. Groundwater movement in the Valley is from southwest to northeast. Major surface discharges of groundwater occur at Rattlesnake Springs (midpoint in the Valley), at points along the Black River, and at Blue Springs.

The upper Black River Valley south and west of Rattlesnake Springs was developed in the 1970's as a natural gas field. After this resource was exhausted in 1981, this area was developed as a natural gas reinjection and storage facility, the Washington Ranch Gas Storage Project. By 1984, a total of 23 gas injection/withdrawal wells have been placed in service within two miles of Rattlesnake Springs.

Groundwater contamination appears to have occurred in several water wells near Rattlesnake Springs starting in 1982 due to leakage of natural gas from several of the gas injection/withdrawal wells. Elevated concentrations of benzene and polycyclic aromatic hydrocarbons have been documented in the impacted wells along with sulfide contamination and accompanying odor and well corrosion.

At issue is whether these contaminants can move through groundwater to Rattlesnake Springs and impact this water source. Rattlesnake Springs lies approximately 1.25 miles north of the gas reinjection area and in the general path of groundwater flow. The goal of this investigation is to assess the potential for natural gas contamination at Rattlesnake Springs and to suggest appropriate remedial action(s).

Colorado State University (CSU) became involved in this potential groundwater contamination problem at Rattlesnake Springs in August, 1987, when Dr. Michael Richard visited the site at the request of the NPS. Dr. Richard made a preliminary assessment at that time that further effort should be made to evaluate potential water contamination at Rattlesnake Springs. The NPS subsequently funded CSU in July, 1988, to conduct a one year investigation of potential contamination by natural gas leakage at Rattlesnake Springs. The goals of the investigation by CSU were as follows:

1. to review existing information on the hydrology and geology of the upper Black River Valley in the vicinity of Rattlesnake Springs to better enable assessment of potential water contamination at the Springs.

2. to visit the site twice during the year to locate and sample available groundwater (existing wells) and to analyze these samples for a number of inorganic and organic parameters. These two sampling trips were conducted in August, 1988, and in March, 1989, coinciding with the historic low and high groundwater flows at Rattlesnake Springs, respectively.

3. to assemble this information into a risk assessment of possible impacts of contamination and their probability at Rattlesnake Springs.

4. to provide the NPS with a review of possible remedial measures that could be taken to prevent or control water contamination at Rattlesnake Springs.

Previous Reports Submitted

Three reports have been submitted to date:

1. Review of the Geohydrology in the Vicinity of Rattlesnake Springs and the Contamination Problem, submitted November 1, 1988.

2. Report of the First Field Investigation, submitted November 1, 1988.

3. Report of the Second Field Investigation, submitted May 15, 1989.

Report Contents

This report presents a review and discussion of analytical findings, some new information not previously reported, a discussion of potential water quality impacts at Rattlesnake Springs should contamination reach the Springs, recommended remedial measures that could be taken at Rattlesnake Springs should contamination reach the Springs, and overall conclusions and recommendations for the investigation.

Review and Discussion of Analytical Findings

Groundwater from a total of 10 wells in the vicinity of Rattlesnake Springs was sampled and analyzed for the following:

1. general water chemistry and major cations and anions: pH, temperature, dissolved oxygen, conductivity, total dissolved solids, alkalinity, hardness, calcium, magnesium, sodium, sulfate, bicarbonate, chloride and chemical oxygen demand (COD);

2. hydrogen sulfide; and

3. benzene, toluene, ethyl-benzene and toluenes (BTEX) by a gas chromatography scan for volatile aromatic hydrocarbons.

The locations of wells sampled are indicated in Figure 2. All wells except the Central Farms-West and the Ballard-7 wells were sampled in August, 1988. All wells except the Sulfur well and the Colwell Ranch well were sampled in March, 1989. These sampling times corresponded to the historic periods of low and high groundwater flow at Rattlesnake Springs, respectively.

Hydrogen sulfide was found in groundwater from the three Ballard wells impacted by natural gas contamination. Hydrogen sulfide was not observed in any of the other groundwaters sampled.

None of the groundwaters sampled, including the Ballard wells, had detectable concentrations of the BTEX compounds -- benzene, toluene, ethylbenzene and toluenes, at both sampling times. Earlier analyses performed in 1984 reported for the Ballard wells found benzene present in the groundwater at 9 - 19 ppb and the presence of polycyclic aromatic hydrocarbons that matched those found in the natural gas being injected.

The impacted Ballard wells were visited three times during this investigation -- in August, 1987, in August, 1988, and in March, 1989. Petroleum and sulfide tastes and odors were evident in Ballard well groundwaters at each visit. Staining by sulfide compounds and significant metal corrosion were also observed at each visit. These visual and sensual impacts of natural gas contamination appeared to lessen at each visit, indicating a lessening of groundwater contamination with time.

Possible groundwater contamination by natural gas was observed at the Smart House well in August, 1987, as a petroleum and sulfide odor in the groundwater and in August, 1988, as well pump corrosion. The Smart House well is located 2/3 of a mile north of the Ballard wells and one mile southwest of Rattlesnake Springs and in the general groundwater flow path towards the Springs. These observations suggest a small, but significant, movement of contaminated groundwater from the impacted Ballard wells to the Smart House well.

The overall inorganic quality of groundwaters sampled is summarized as Stiff diagrams in Figure 3. Here, concentrations of the three most significant cations and anions (in milliequivalents per liter - meq/l) are plotted along parallel horizontal axes with the cations and anions plotted on either side of a vertical zero axis. The resulting points are connected to yield a polygonal pattern, distinctive for waters of differing composition. The width of the pattern is an approximate indicator of the total ionic content of the water (correlates with total dissolved solids or ionic conductivity).

From Figure 3 it can be seen that groundwater at the Colwell Ranch well, the Central Farms-West well, Rattlesnake Springs and the CARC well are all similar in inorganic composition, all being a calcium-bicarbonate type water. Rattlesnake Springs, the Central Farms-West well and the CARC well are all documented to be hydraulically connected. Groundwaters at the Smart House and Irrigation wells are similar to the above, but differ in having more sulfate in the Smart Irrigation well water and more magnesium in the Smart House well water. The Smart Irrigation well water is classed as a calcium-sulfate water while the Smart House well water is classed as a magnesium-bicarbonate water.

These water quality findings follow closely the historic sulfate content of groundwaters near Rattlesnake Springs, shown in Figure 4. Groundwater at Rattlesnake Springs appears to consist of a mixture of groundwater sources in the area. Groundwater at Rattlesnake Springs has slightly more mineral content than the nearest well downgradient (the Central Farms-West well) but much less mineral content than found at the Ballard wells, southeast of Rattlesnake Springs. The CARC well, located south of Rattlesnake Springs, has a slightly higher mineral content than found at Rattlesnake Springs, suggesting more contribution to the CARC well of higher sulfate content groundwater from the south.

Sulfate content of groundwater at Rattlesnake Springs could serve as an indicator of the contribution of groundwater from the south, where natural gas contamination has occurred. The sulfate content of water at Rattlesnake Springs is normally low and in the range 110-150 mg/L. However, more of the high sulfate groundwater from the south may reach Rattlesnake Springs at certain times, dependent on variable groundwater recharge and flow pattern in the area. This was observed in 1975 when the sulfate concentration at Rattlesnake Springs reached 300 mg/L. Thus, a possible hydraulic connection of Rattlesnake Springs to higher sulfate groundwater to the south, where groundwater contamination has occurred, may exist.

Conclusions based on available information are: (1) that natural gas contamination from leaking injection/withdrawal wells occurred at the Ballard wells in 1982; (2) that this contamination either remained localized or moved downgradient to possibly impact the Smart House well but not any wells further north including Rattlesnake Springs; and (3) that no contamination has been observed at Rattlesnake Springs due to groundwater contamination at the Ballard wells.

New Information

Groundwater Recharge Rate Near Rattlesnake Springs

A close relationship was found to exist between rainfall and water levels in three wells located nearest to Rattlesnake Springs. Monthly total rainfall is plotted against groundwater level for the CARC well (25.24.26.121), the Central Farms well (25.24.27.421) and the Central Farms-West well (25.24.27.124) in Figures 5 - 7 for the period January, 1952 (month 1), to December, 1962 (month 132) or 1964 (month 156). Although these figures are difficult to interpret due to the quantity of data shown, there exists a close association between monthly rainfall amount and depth to groundwater for each of the three wells. This relationship is better illustrated in Figure 8 where the groundwater level and monthly total rainfall is shown for the CARC well (121) for the years 1959, 1961, 1962 and 1960 (years when the records are available). Here it can be seen that groundwater levels respond rapidly to rainfall events, rising within 2 - 4 months after major rainfall periods or events.

This finding indicates a rapid recharge of groundwater after rainfall events and a corresponding rapid movement of groundwater in the upper Black River Valley near Rattlesnake Springs. This observation is significant as groundwater contamination, if present, would be expected to move rapidly through the aquifer(s) near Rattlesnake Springs, reaching the Springs in less than one year.

Possible Impact of Natural Gas Contamination in the upper Black River Valley at Blue Springs

Wells at Blue Springs, the most downgradient surface discharge point for groundwater in the upper Black River Valley, became contaminated by hydrogen sulfide in the summer of 1988. A speculative conclusion, not documented, is that natural gas contamination originating at the Ballard wells moved northeastward, by-passed Rattlesnake Springs to the south, and subsequently impacted wells at Blue Springs approximately 20 miles downgradient of Rattlesnake Springs. If this speculation is correct, then the threat to Rattlesnake Springs from contaminated groundwater originating at the Ballard wells was real.

Projected Impact of Natural Gas Contamination at Rattlesnake Springs

Four main chemical groups occur in natural gas (and petroleum) of concern if these contaminate drinking water. These are: (1) alkane and acyclic hydrocarbons; (2) aromatic hydrocarbons; (3) polycyclic aromatic hydrocarbons; and (4) sulfides. A summary of the toxicity concerns and concentrations of concern for each of these chemical groups is given in Table 1.

Contamination of the Ballard wells by natural gas has resulted in low concentrations of aromatic hydrocarbons, primarily benzene, and polycyclic aromatic hydrocarbons, and higher concentrations of sulfides in the well water. Sulfide may originate in the natural gas (soured gas) or may be produced in soil and groundwater by bacterial reduction of sulfate used as an "oxygen" source during the biooxidation of methane. This latter source of sulfide is the cause of high sulfide in the Ballard wells.

If natural gas contamination were to reach Rattlesnake Springs, impacts on water quality would be similar to those observed at the Ballard wells. Compounds of toxicological concern such as aromatic hydrocarbons (benzene) and polycyclic aromatic hydrocarbons could be present in the groundwater at low concentration. These compounds are of concern as possible human carcinogens if consumed at low concentration over an extended period of time (years).

The most significant impact of contamination at Rattlesnake Springs would be from sulfide. Aesthetic and economic impacts would be most noticed. Tastes and odors would be offensive while corrosion of metal components in the well and in the water transmission and distribution system would be severe.

The economic impact of corrosion would probably be the most significant impact of contamination at Rattlesnake Springs.

Recommended Remedial Measures to be Taken at Rattlesnake Springs Should Contamination Arrive

Arrival of contaminated groundwater at Rattlesnake Springs would first be detected by the presence of sulfide. Free chlorine reacts rapidly with sulfides to produce chloride ion and sulfur and sulfate. Low concentrations of sulfides would automatically be oxidized by free chlorine now applied to Rattlesnake Springs groundwater for disinfection without any apparent effects other than increased chlorine usage. This would be observed as a need to increase the chlorine dosage to maintain a desired free chlorine residual. Sulfide odor would be apparent at the well before chlorine addition.

More extensive groundwater contamination would require additional water treatment steps to be taken at Rattlesnake Springs. The most appropriate treatment process would be granular activated carbon (GAC) filtration before chlorination. This treatment process would remove petroleum tastes and odors and aromatic hydrocarbons such as benzene. Chlorination after GAC filtration would effectively remove any remaining sulfide.

It is recommended that the GAC filtration system, should it be required, be purchased as a package from a national supplier who would provide correct sizing, installation, operational instruction, and routine replacement of the spent GAC medium when required.

Conclusions

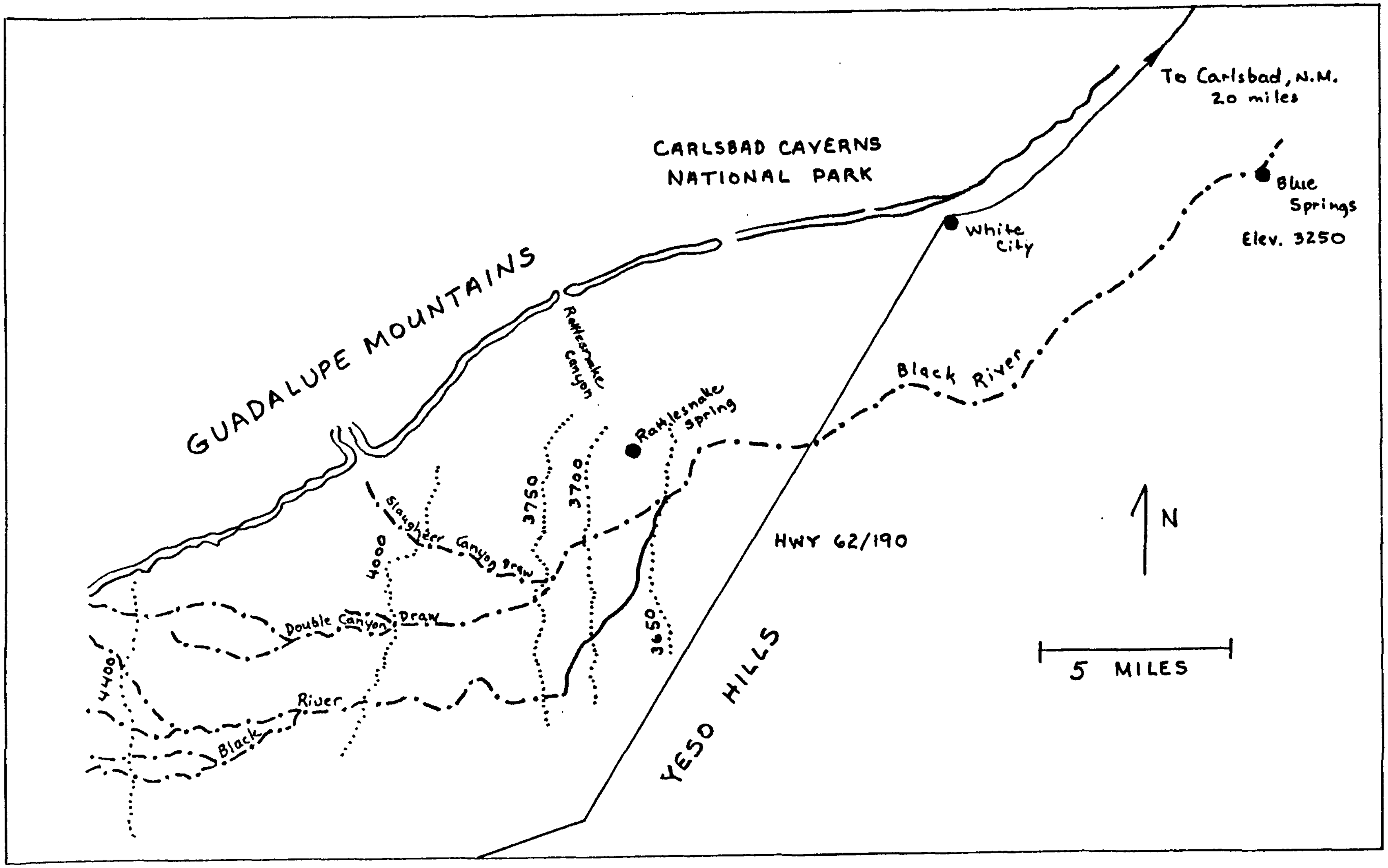
Groundwater contamination by natural gas compounds occurred in the upper Black River Valley in 1982 most likely due to several leaking natural gas injection/withdrawal wells, which have since been repaired. This resulted in local groundwater contamination by benzene, polycyclic aromatic hydrocarbons and sulfide in the vicinity of the Ballard wells. Contamination appears at this time to have lessened at the Ballard wells. No evidence of contamination has been found at wells nearer to Rattlesnake Springs than the Smart House well and may not have reached wells hydraulically connected to Rattlesnake Springs. Given the rapid hydraulic transit times of groundwater near Rattlesnake Springs, on the order of months, it is concluded that groundwater contamination has dissipated or by-passed Rattlesnake Springs. There does not appear to be any significant contamination threat to Rattlesnake Springs at this time.

It is interesting to speculate that the severe well contamination by sulfides that occurred at Blue Springs in the summer of 1988 was related to the contamination at the Ballard wells. Blue Springs is located approximately 20 miles downgradient of Rattlesnake Springs and is the terminal surface discharge point of the upper Black River Valley aquifer. It may be that contaminated groundwater from the Ballard wells by-passed Rattlesnake Springs to the south and impacted water supplies downgradient. Thus, there appears to have been a real threat of contamination at Rattlesnake Springs and a near contamination event that would have had severe impact on the operation of Carlsbad Caverns National Park.

Recommendations

1. No further special effort in monitoring groundwater near Rattlesnake Springs appears warranted at this time. Regular monitoring of well water at Rattlesnake Springs should be conducted for sulfide on a biweekly basis and BTEX on a six month basis.
2. A working relationship should be established between the El Paso Natural Gas Company and the National Park Service to keep the National Park Service informed of any new gas well development or problems with existing reinjection wells. In the event of future groundwater contamination problems, which could occur at any time, a groundwater monitoring program should be initiated based on the sites and types of analyses used in this investigation.

Figure 1. Topographical Features of the Upper Black River Valley, New Mexico.



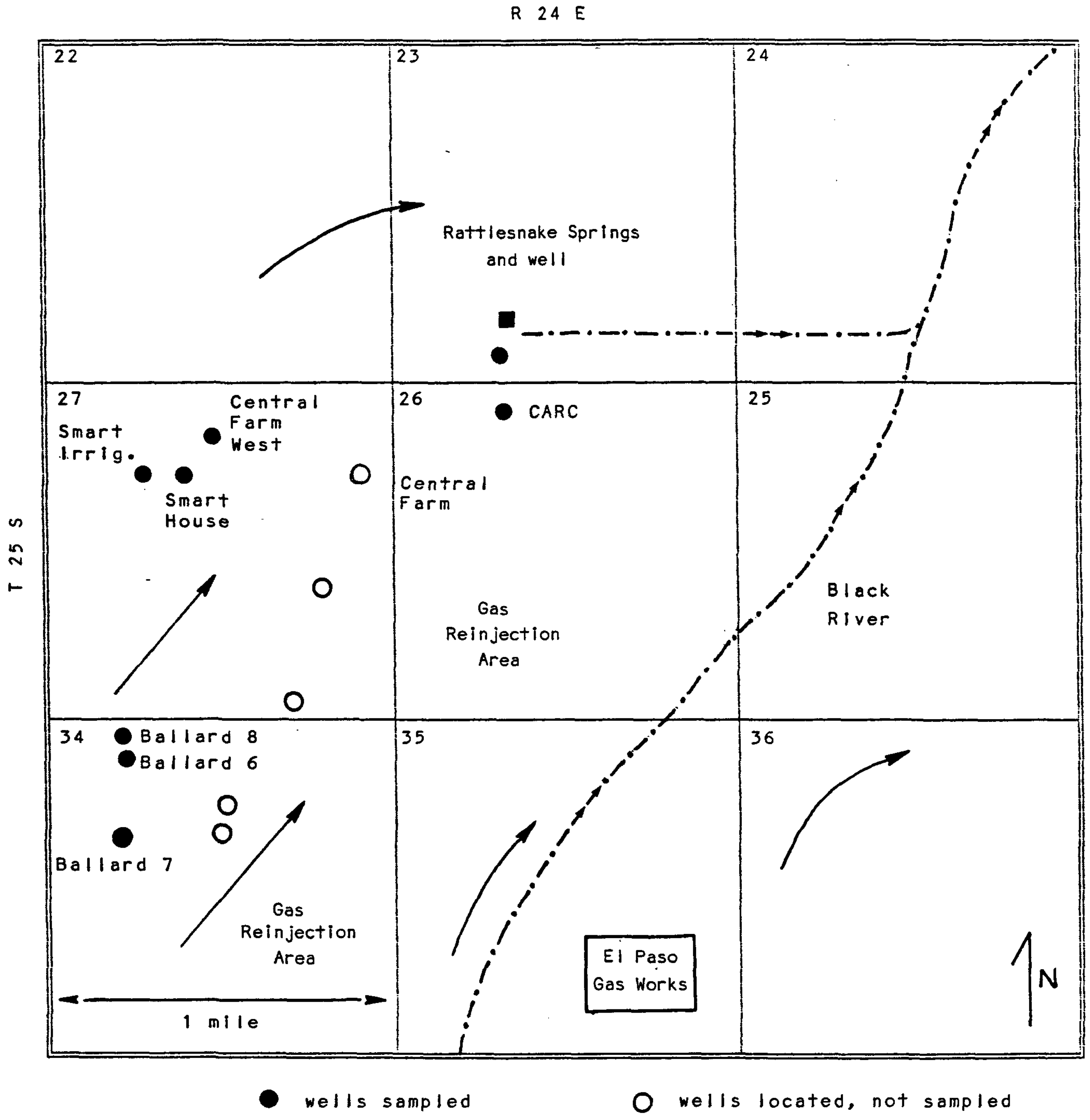


Figure 2. Location of Wells Sampled and Generalized Groundwater Flow in the upper Black River Valley.

Figure 3. Stiff Diagrams for Groundwaters Sampled in the Upper Black River Valley.

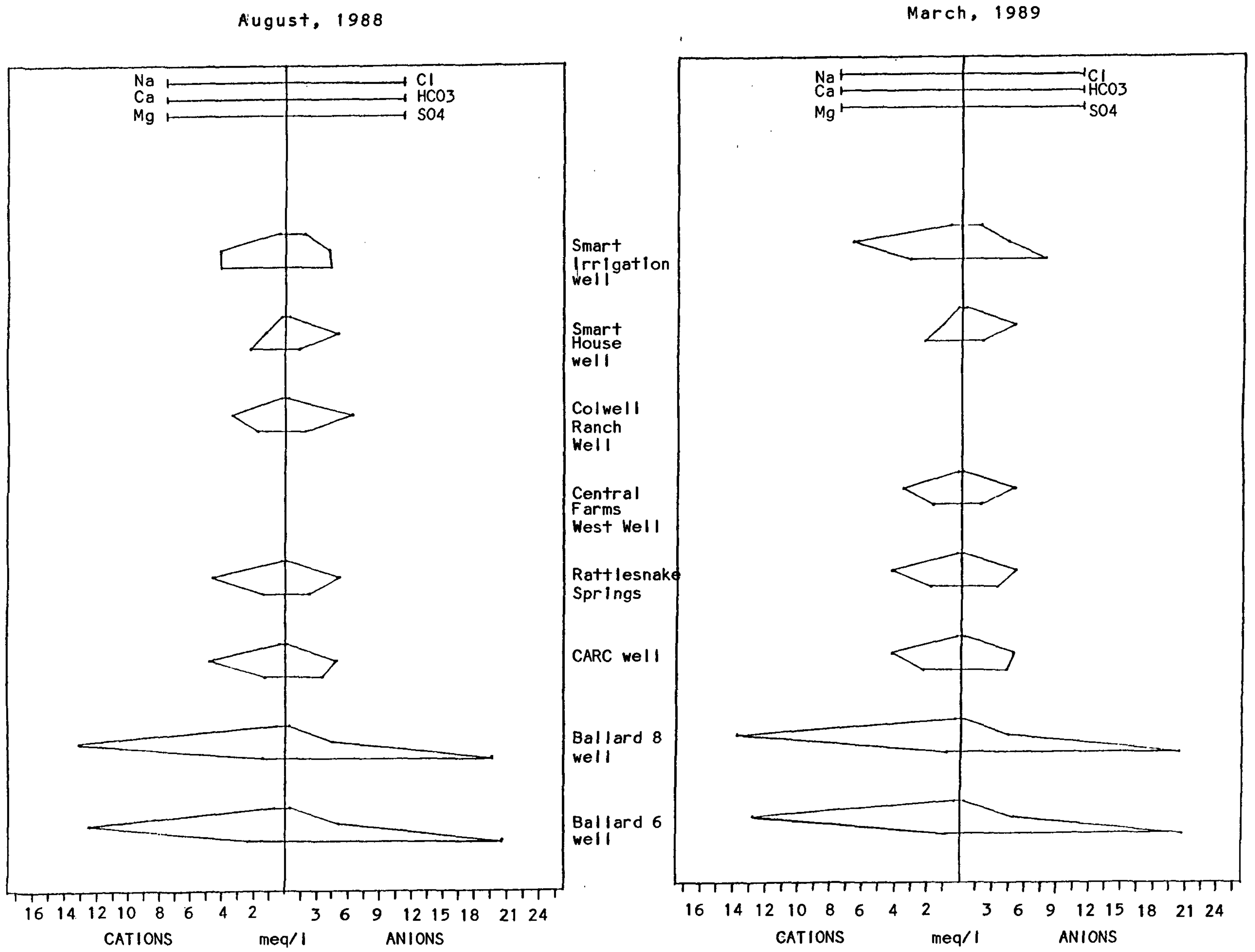


Figure 4. Major Geologic Features and Sulfate Content of Groundwaters in the Upper Black River Valley.

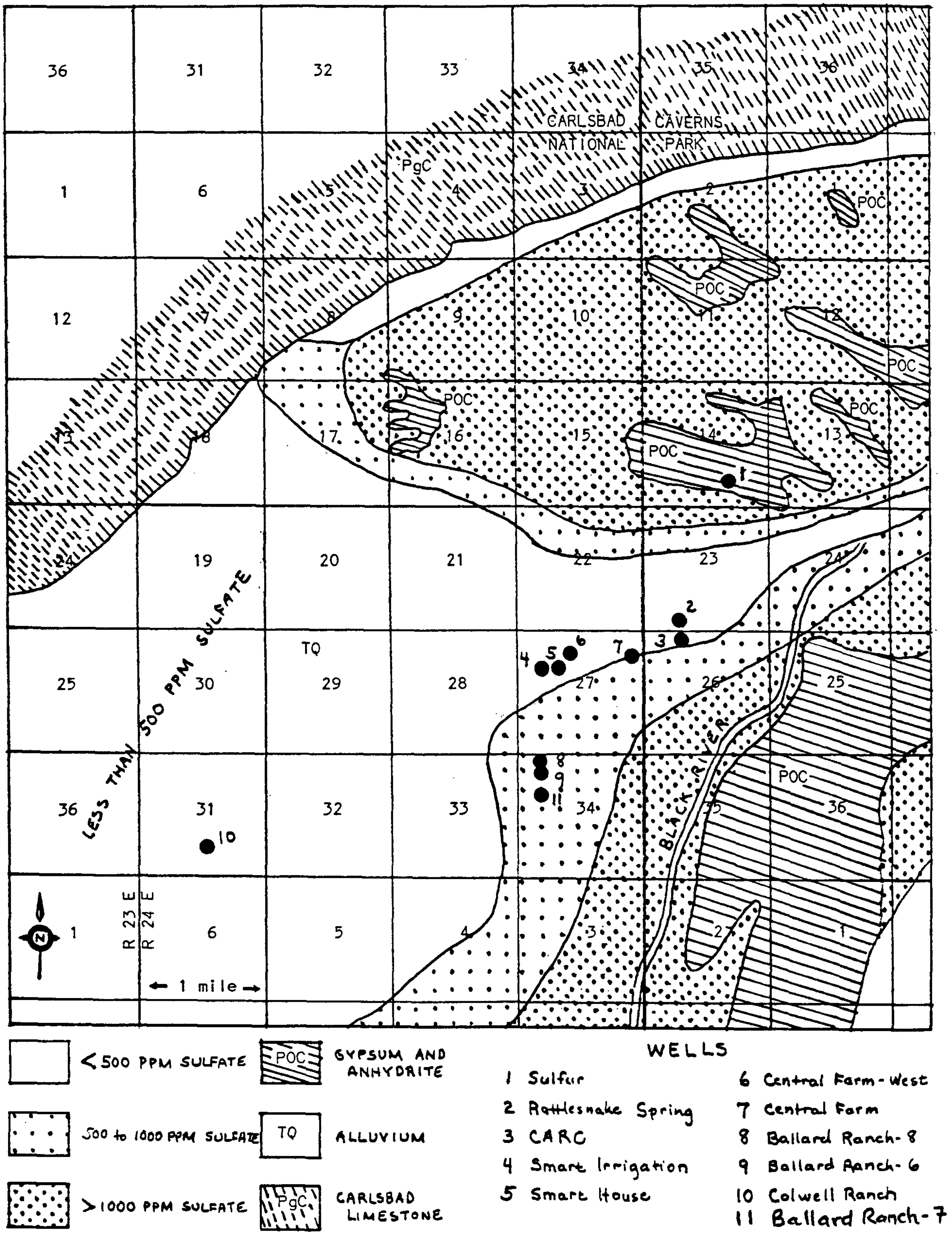


Figure 5. Relationship of Total Monthly Rainfall to Groundwater Elevation for the CARC Well for the Period 1952 to 1964.

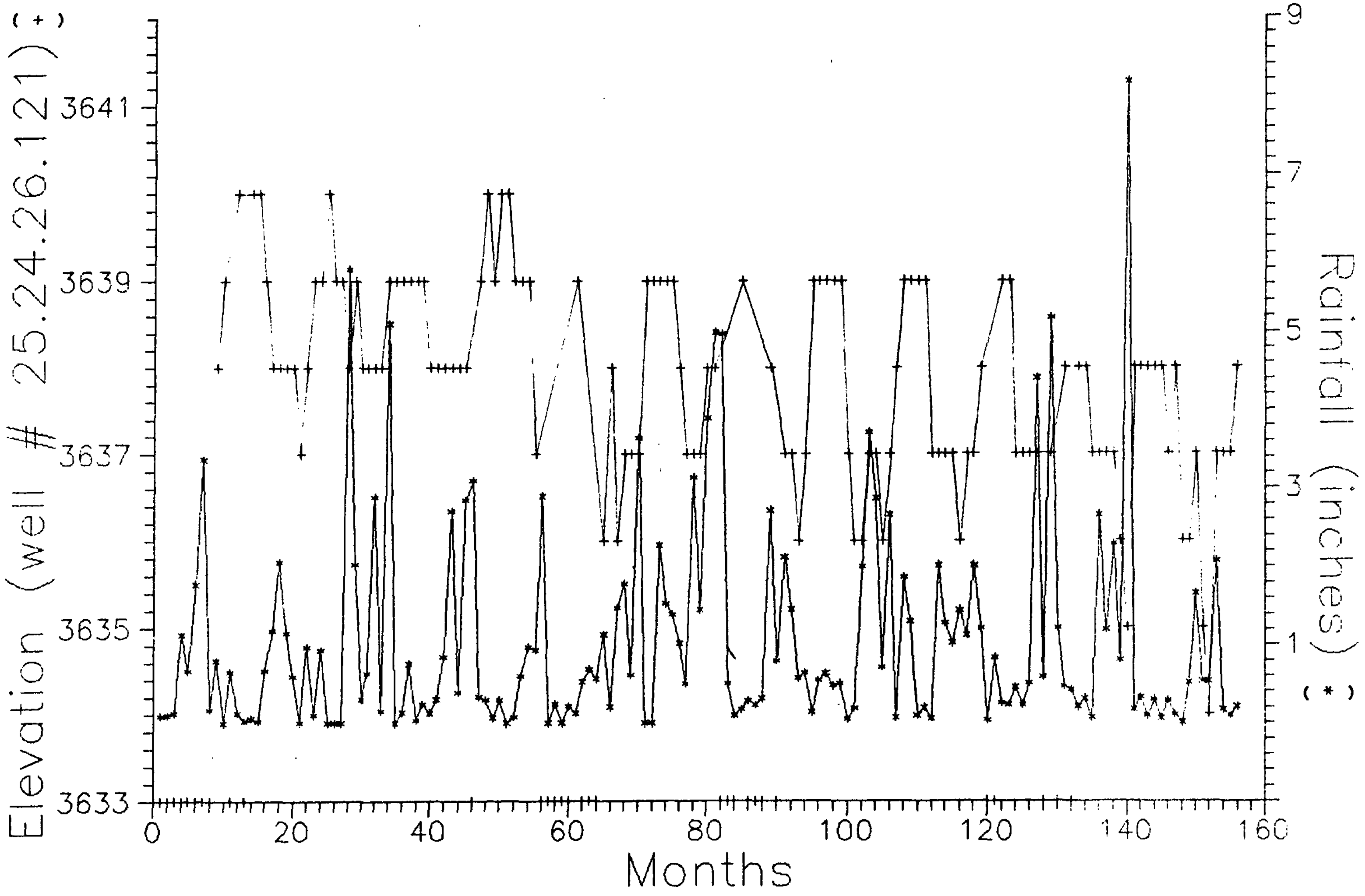


Figure 6. Relationship of Total Monthly Rainfall to Groundwater Elevation for the Central Farms Well for the Period 1952 to 1962.

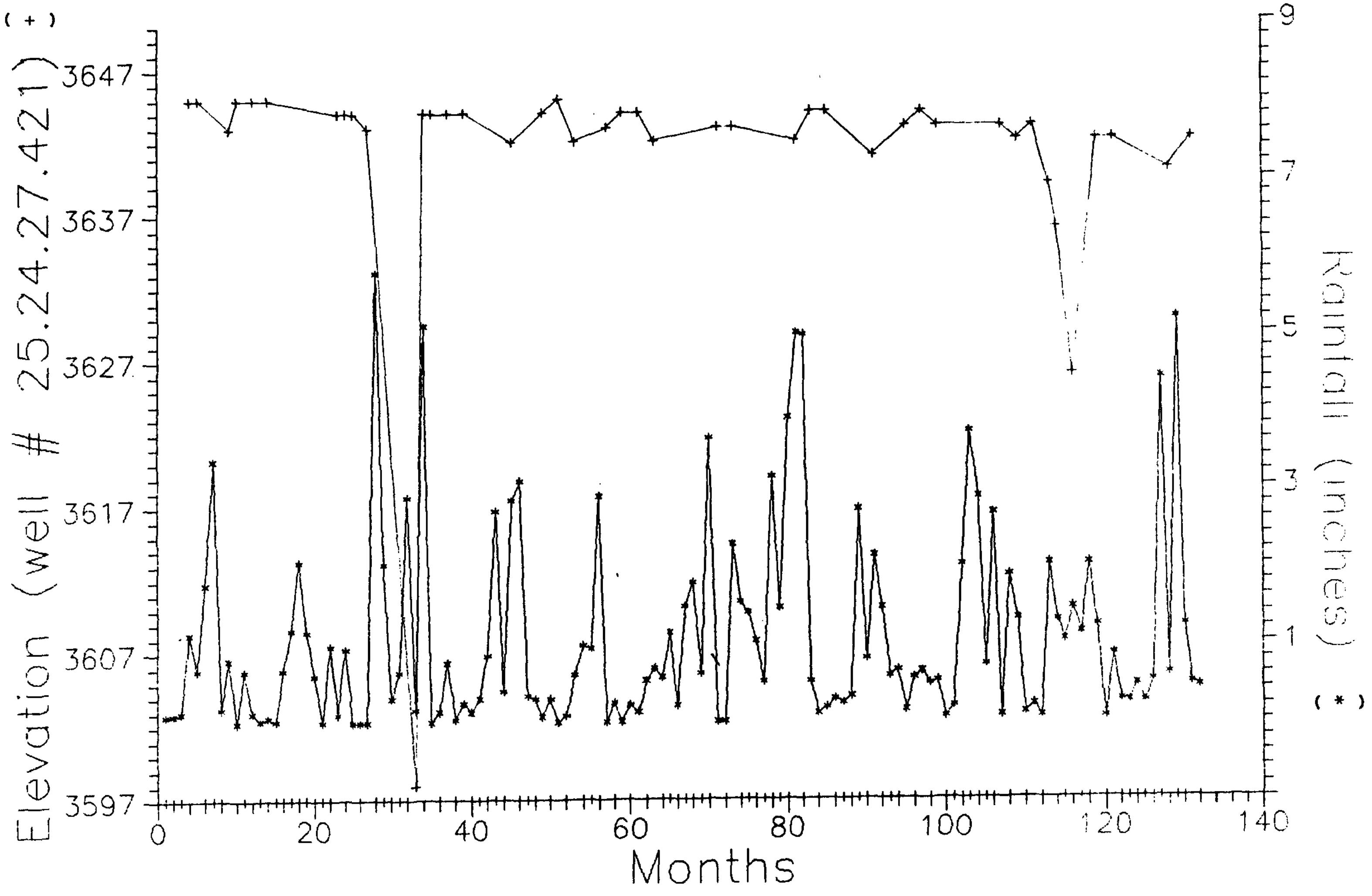


Figure 7. Relationship of Total Monthly Rainfall to Groundwater Elevation for the Central Farms-West Well for the Period 1952 to 1962.

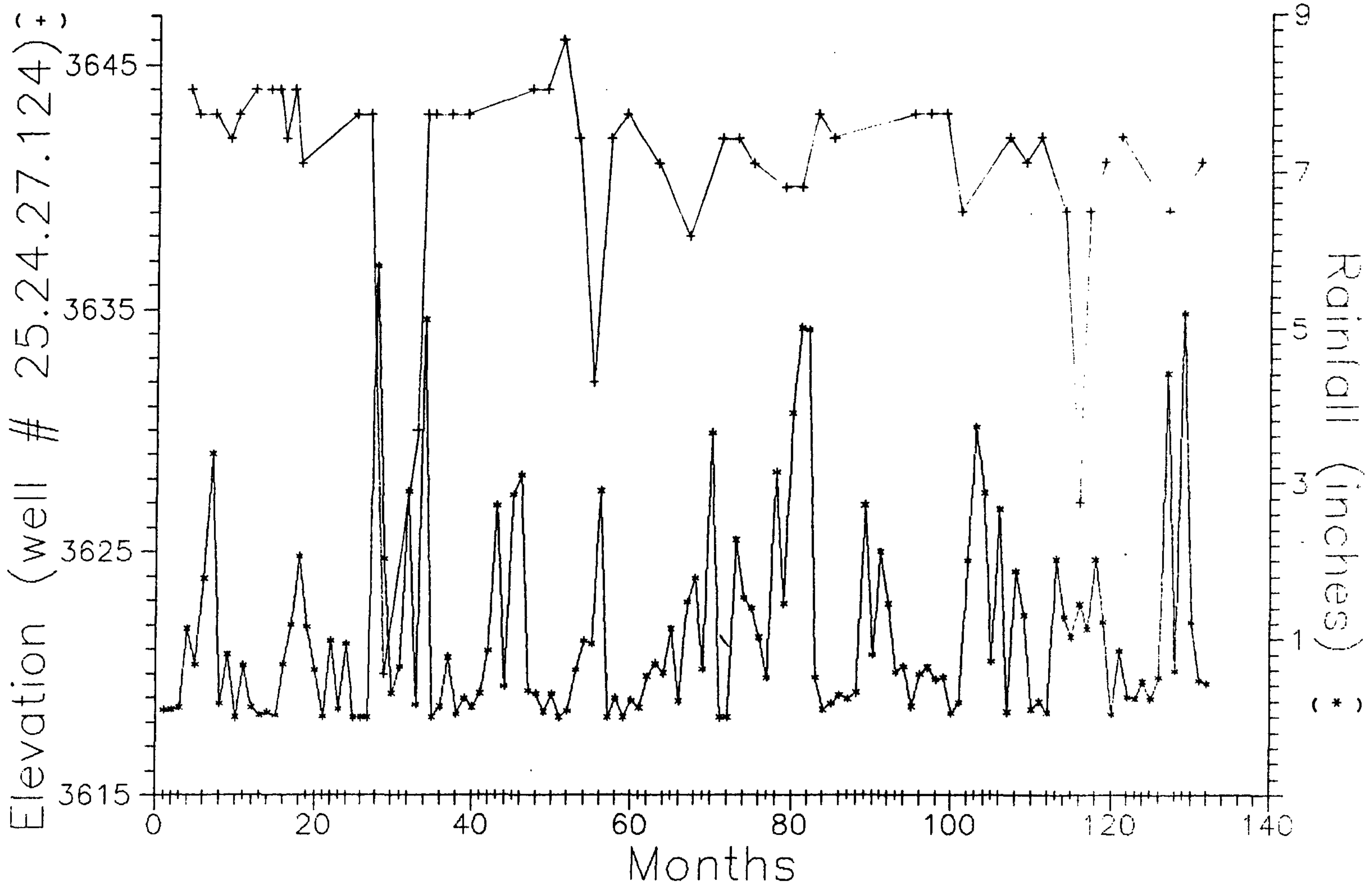


Figure 8. Relationship of Total Monthly Rainfall to Groundwater Elevation for the CARC Well for the Years 1959, 1960, 1961 and 1962.

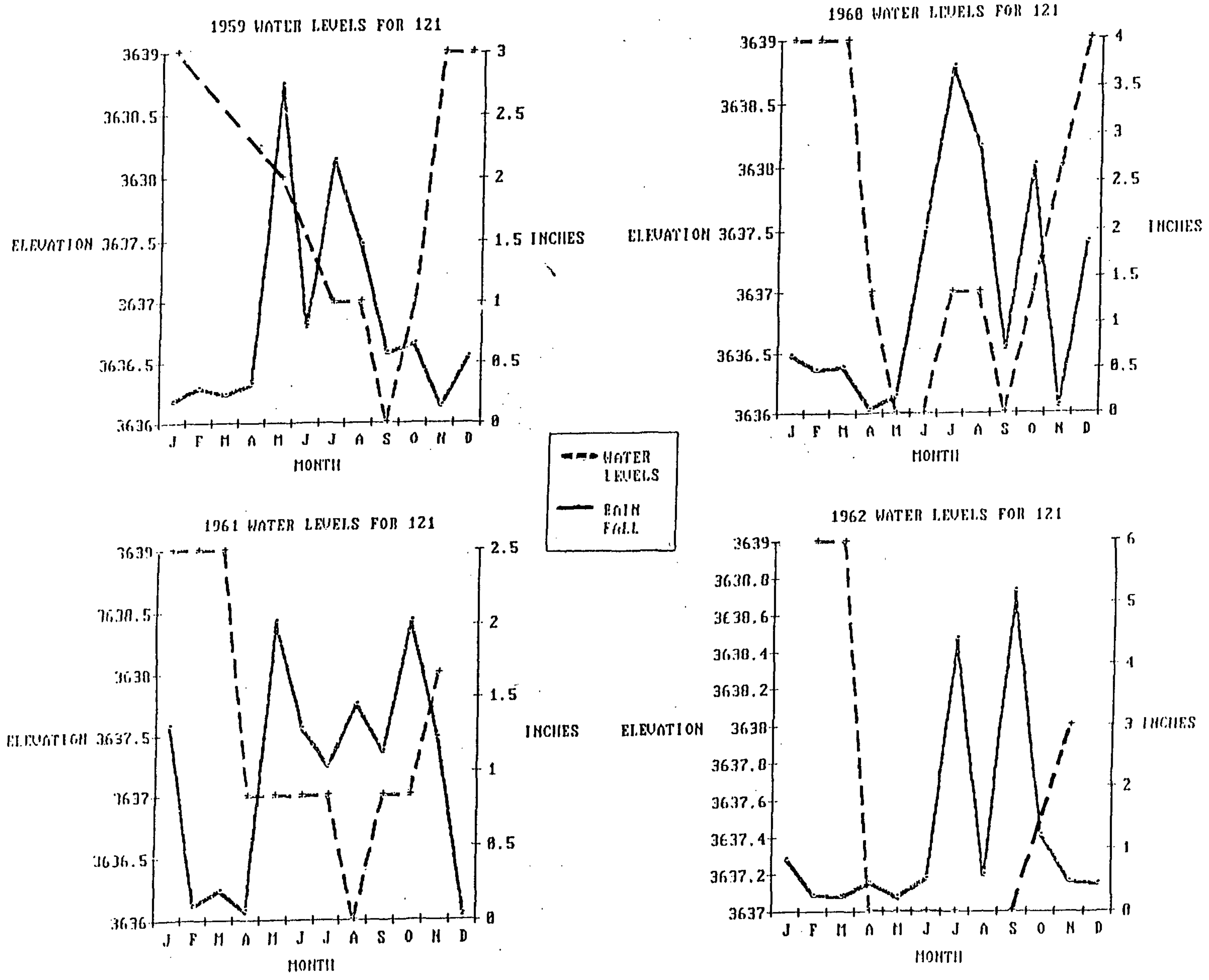


Table 1. Groundwater Contamination Concerns for Natural Gas and Crude Petroleum.

COMPONENT GROUP	CONSTITUENTS	WATER SOLUBILITY	TOXICITY CONCERNS	EXPECTED BACKGROUND LEVELS PPB	CONCENTRATIONS OF CONCERN
1. alkane and acyclic hydrocarbons	C1 - C40 hydrocarbons	very low	little acute toxicity; narcotic and irritant effects at high concentration	-	-
2. aromatic hydrocarbons	diverse types (small to 20% of total); benzene, toluene and ethylbenzene most common	low, but significant. Benzene most water soluble of compounds (0.82 g/L)	benzene is a hematoxin and human carcinogen.	<0.01 - 0.03	for benzene: SNARL* = 250 ppb MCL** for drinking water = 5 ppb
3. polycyclic aromatic hydrocarbons (PAH)	more than 50 compds. consisting of substituted and unsubstituted polycyclic and heterocyclic aromatic rings (2 or more); e.g. naphthalene	extremely low	some components are human carcinogens acute aquatic toxicity in the range 0.1-0.5 ppm	< 0.1	no U.S. standards WHO recommends a drinking water limit of 0.2 ppb
4. sulfides	H_2S, mercaptans	high, to 500 mg/L for H_2S	acutely toxic corrosive offensive odor at ppb levels	-	Threshold odor concentration = 0.025-0.25 ppb

* SNARL = 7 day suggested no adverse response level. ** new federal standard for public and noncommunity water supplies to take effect early in 1989.

Shomaker

Bacterial production of methane and its influence on ground-water chemistry in east-central Texas aquifers

Ethan L. Grossman, B. Keith Coffman
Department of Geology, Texas A&M University, College Station, Texas 77843
Steven J. Fritz
Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, Indiana 47097
Hideki Wada
Institute of Geosciences, Shizuoka University, Shizuoka City 422, Japan

ABSTRACT

Geochemical and isotopic data for methane and ground water indicate that gaseous hydrocarbons in Eocene aquifers in east-central Texas form by bacterial processes. The $\delta^{13}C$ values of methane from five wells in the clay-rich Yegua and Cook Mountain Formations range from −71‰ to −62‰. Methane from ten wells in the cleaner sands of the Sparta and Queen City Formations have $\delta^{13}C$ values between −57‰ and −53‰. The carbon isotopic difference between methanes from the Yegua and Sparta aquifers is comparable to the isotopic difference in sedimentary organic matter from outcrops of the units, suggesting substrate control on the $\delta^{13}C$ of bacterial methane. Hydrogen isotopic compositions of methane from the aquifers are similar, averaging −181‰. This high value suggests methane production predominantly by CO_2 reduction.

The $\delta^{13}C$ of dissolved inorganic carbon (DIC) in high bicarbonate waters increases from about −20‰ to 0‰ with increasing DIC. Mass-balance calculations indicate that the DIC added to the ground water has $\delta^{13}C$ values as high as 10‰. This ^{13}C-enriched carbon is predominantly derived from CO_2 production by fermentation and anaerobic oxidation reactions combined with CO_2 consumption by CO_2 reduction. This process is responsible for high bicarbonate contents in these and probably other Gulf Coast ground waters.

INTRODUCTION

Methane in aquifers can be a resource, a prospecting tool, or a hazard, and can have a significant impact on ground-water carbon budget and ^{14}C activity. In east-central Texas ground water, gaseous hydrocarbons occur in prodigious quantities. By studying the chemistry of these hydrocarbons and associated ground water, it is possible to develop a fundamental understanding of methanogenesis and its effect on ground-water chemistry.

Gaseous hydrocarbons in the Eocene aquifers of east-central Texas may be produced in situ by bacteria using substrates derived from lignite or disseminated organic matter. In general, the predominant methanogenic pathways are CO_2 reduction,

$$CO_2 + 4H_2 \rightarrow 2H_2O + CH_4,$$

and acetate dissimilation or fermentation,

$$CH_3COOH \rightarrow CH_4 + CO_2$$

(e.g., Wolin and Miller, 1987). Methane may also migrate into the aquifer, either naturally or through leaks in production well casings. Production of thermocatalytic gas from Cretaceous and Eocene reservoirs in the study area enhances this possibility. Bacterial methane may also migrate into an aquifer from sanitary landfills or other aquifers.

Carbon isotopes can be used to differentiate between bacterial and thermocatalytic methane (Stahl, 1974; Bernard et al., 1977; Schoell, 1983; among others). Thermocatalytic methane tends to have $\delta^{13}C$ values between −50‰ and −25‰, whereas bacterial methane tends to have values between −90‰ and −55‰. According to Whiticar et al. (1986), methanogenic pathways can be distinguished by carbon and hydrogen isotopic composition of methane. They propose that methane in marine sediments, formed principally by CO_2 reduction, tends to have $\delta^{13}C$ values between −110‰ and −60‰ and δD values between −250‰ and −170‰; methane from fresh-water sediments, which Whiticar et al. (1986) attributed to acetate fermentation, tends to have $\delta^{13}C$ values between −65‰ and −50‰ and δD values between −400‰ and −250‰. Bacterial oxidation of methane can enrich residual methane in ^{13}C and deuterium (Coleman et al., 1981) and confound genetic interpretation of isotope data.

The proportion of ethane and higher hydrocarbons (C_{2+}) to methane (C_1) can also be used to distinguish gaseous hydrocarbons of different origins. Bacterial gases have C_1/C_{2+} ratios of at least 100 and generally more than 1000 (Stahl, 1974; Schoell, 1983); thermocatalytic gases tend to have C_1/C_{2+} ratios of less than 50 (Bernard et al., 1977). Migration will increase the C_1/C_{2+} ratio of gaseous hydrocarbons (Coleman et al., 1977), making it difficult to discriminate between bacterial gas and migrated thermocatalytic gas. Fortunately, these "dry" thermocatalytic gases can be readily distinguished from bacterial gases by carbon isotopic composition, which is essentially unchanged by migration (Fuex, 1980).

Isotopic studies of gaseous hydrocarbons in ground water are few, which is surprising considering the size and importance of the system. Coleman (1976) used the $\delta^{13}C$ of methane and C_1/C_{2+} ratios to determine the origin of gaseous hydrocarbons in glacial drift and sedimentary rock in Illinois. Barker and Fritz (1981) combined isotopic and concentration data for methane with chemical and isotopic analyses of water to characterize the origin of ground-water methane in Ontario, Manitoba, and North Dakota.

In a different approach, Chapelle and Knobel (1985) used mass-balance calculations of carbon isotopes in dissolved inorganic carbon (DIC) to argue that methanogenesis produces ^{13}C-enriched carbon in the Aquia aquifer in Maryland. Chapelle et al. (1987, 1988) substantiated this proposal by demonstrating the presence of viable methanogenic bacteria in cores of deep coastal plain sediments from the eastern United States. Grossman et al. (1986) reached a similar conclusion for the origin of methane in the Sparta aquifer in east-central Texas. High DIC $\delta^{13}C$ ($\delta^{13}C_{DIC}$) values in methane-bearing, high-bicarbonate waters indicated a source of ^{13}C-enriched CO_2 best explained by CO_2 production in association with methanogenesis.

Whether this ^{13}C-enriched CO_2 is derived from acetate dissimilation or CO_2 reduction is unclear. At first glance it appears that CO_2 reduction should consume CO_2 (and thus decrease DIC) and acetate dissimilation should produce it. However, these reactions represent only the final step of a series of reactions. In the complete breakdown of a compound like glucose, similar amounts of CO_2 are produced whether the reaction follows the CO_2 reduction pathway or the acetate dissimilation pathway (see Klass, 1984).

STUDY AREA

The principal aquifers studied—the Queen City, Sparta, and Yegua—are formations of the Eocene Claiborne Group and crop out in a northeast-southwest strike in east-central Texas (Fig. 1). In the study area the Claiborne Group is about 790 m thick with a southeast dip of about 19 m/km (Follett, 1974). Of the three formations, the Queen City Sandstone is the lowest stratigraphically. The unit is bounded by Reklaw clays below and Weches glauconitic clay above, and is about 70 m thick in Robertson County. Its lithology consists of about 70% sand, 22% sandy silty clay, 5% glauconite, 1% lignite, and 1% bentonite (Sellards et al., 1932). The Sparta Sandstone is similar to the Queen City Formation in lithology, environment of deposition, and hydrology. The formation is sandwiched between the clay-rich Cook Mountain and Weches Formations and is about 61 m thick in the study area. The Yegua Formation overlies the clays and sands of the Cook Mountain Formation, and underlies the marine sediments of the Jackson Group. The unit is much thicker (about 335 m in the study area) and more clay rich than the Sparta and Queen City Sandstones.

The Queen City aquifer, with a mean transmissivity of 67 m^2/day in nearby Leon County, serves a principal aquifer in the study area (Follett, 1974; Fogg and Kreitler, 1982). Short transit times result in fresh to slightly saline waters. The Sparta Sandstone is a principal aquifer in Brazos County and has a mean transmissivity of about 177 m^2/day (Follett, 1974). The high clay content of the Yegua results in its being only a secondary aquifer, capable of yielding small to moderate quantities of fresh to moderately saline water. Pump tests on one well in the Yegua indicate a transmissivity of only 2 m^2/day (Follett, 1974). In the confined parts of these aquifers, hydraulically driven flow is generally downdip.

METHODS

Water was sampled from wells screened at 24–610 m (78–2000 ft) in the Yegua, Queen City, Sparta, Cook Mountain, and Reklaw Formations (Fig. 1, Table 1). Effort was made to sample wells producing gas-rich water. Other wells were sampled to provide a good geographic and depth distribution. The Sparta wells were sampled to augment the data set of Grossman e al. (1986), which includes 24 Sparta wells and Yegua well. With one exception, all the Spart waters sampled contained a gas phase. Gaseou hydrocarbons were sampled from two gas production wells completed in the Cretaceou Woodbine Formation and located near well producing gas-rich water (Fig. 1). To characterize sedimentary organic matter which might provide a substrate for bacteria, three thin lignit seams (2–5 cm) were sampled from the Yegu Formation, and a 3-cm-thick black shale be was collected from outcrops 20 m apart in th Sparta Sandstone (Fig. 1).

Except for artesian wells, each water well wa purged of stagnant water for 45–60 min befor sampling. Most wells had to be sampled down line from the pressure tank. Pressure tanks utiliz a diaphragm to separate ground water from th overlying air, but some degassing may occur Seven of the deepest wells had steel casings. Th remainder were cased with PVC plastic. No relation was observed between casing material o location of sample spigot, and water and gas chemistry.

Water samples for isotopic measurement o DIC were collected in 16 ml glass vials with poly-seal caps, and dissolved hydrocarbon samples were collected in Coca-Cola bottles. These samples were refrigerated upon return from the field. When waters were gas-rich, gas (termed head gas) was collected in Mason jars according to the method of Coleman (1976) and refrigerated inverted.

Temperature and pH were measured at the well site. Alkalinity titrations, used with pH to calculate DIC, were performed immediately upon arrival in the laboratory. Cation concentrations (Na^+, K^+, Ca^{2+}, Mg^{2+}, and Fe_{total}) were determined by atomic absorption spectrophotometry, and sulfate and chloride were measured using turbidimetric and titrimetric methods, respectively. Hydrocarbon concentrations were determined by gas chromatography by using a flame ionization detector. Dissolved hydrocarbons were stripped using the method of McAuliffe (1966). Head-gas hydrocarbons were measured directly within 12 h of sampling. Carbon dioxide was stripped from ground water by acidification and in vacuo stripping. Head-gas methane samples were combusted for isotopic analysis within 12 h of sampling by passing the gas through an 850 °C furnace. Lignite samples were pretreated with 3N HCl before 850 °C combustion in sealed tubes. Water samples and waters of combustion were reduced to hydrogen for isotopic analysis using zinc at 450 °C (Coleman et al., 1982). All isotopic measurements were conducted on Finnigan MAT 251 isotope ratio mass spectrometers. The $\delta^{13}C$ and δD values are reported vs. the PDB (Peedee belemnite) and SMOW (standard mean ocean water)

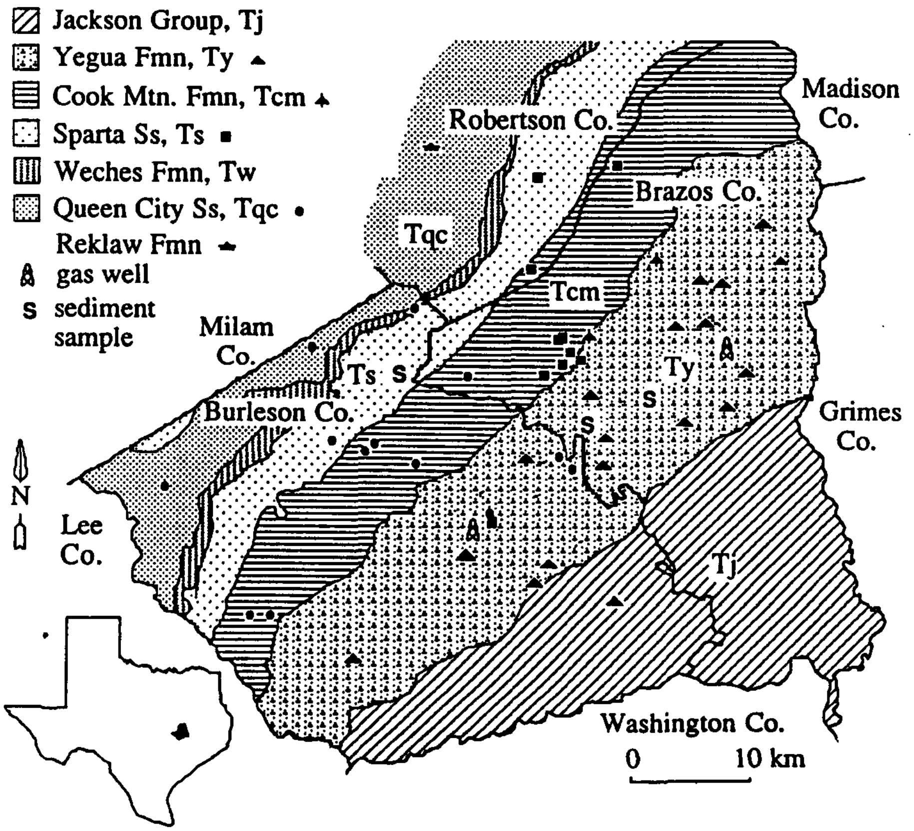


Figure 1. Index map showing well locations and outcrop patterns of Queen City, Sparta, and Yegua Formations in Brazos, Burleson, and southern Robertson counties, Texas.

standards, respectively. Precision was ±0.1‰ for $\delta^{13}C$ analyses and ±2‰ for δD analyses.

RESULTS AND DISCUSSION

Gaseous Hydrocarbons

Of the 45 wells sampled, 16 yielded appreciable methane-bearing head gas. Methane and ethane were the only hydrocarbon species detected in these head gases. Their concentrations in terms of total gas ranged from 13.2 to 33.4 mmol/l and 0.68 to 17.3 μmol/l, respectively. The C_1/C_{2+} ratios for the hydrocarbons in these samples are all greater than 1000; some approach 20000 (Fig. 2). These values are indicative of bacterial gas, or thermocatalytic gas which has undergone migration. The geographic distribution of methane-bearing waters does not follow any distinctive pattern, and cannot be readily correlated with oil production wells or landfills.

Waters with head gas exhibited dissolved methane and ethane concentrations ranging from 350 to 1733 μmol/l and 0 to 0.835 μmol/l, respectively (Table 1). At formation temperatures, the saturation value is about 1400 μmol/l for methane and about 1900 μmol/l for ethane (McAullife, 1966). Thus, in waters with head gas, dissolved methane concentrations are at or near saturation, whereas ethane concentrations are well below saturation. In waters without head gas, dissolved methane concentrations range from 0.1 to 6.1 μmol/l. Only eight of these well waters contained detectable ethane, with values from 0.002 to 0.066 μmol/l.

Carbon isotopic compositions for methane ($\delta^{13}C_{C1}$) in the Yegua and Cook Mountain aquifers range from −71.4‰ to −61.6‰, averaging −65.2‰ (Table 1, Fig. 2). These values indicate a bacterial source for the methane, an interpretation consistent with the C_1/C_{2+} data. Methane from the well in the Reklaw Formation gave a $\delta^{13}C$ value of −64.6‰, suggesting the same origin as Yegua-Cook Mountain gas. The Sparta and Queen City aquifers yield methane enriched in ^{13}C relative to Yegua-Cook Mountain gas, with values ranging from −58.4‰ to −53.1‰ and averaging −54.6‰. These higher $\delta^{13}C_{C1}$ values could arise from input of thermocatalytic gas, oxidation of methane by methanotrophic bacteria, differences in methanogenic pathway, or differences in the $\delta^{13}C$ of the substrate.

Thermocatalytic gas produced in the area has a ^{13}C composition of −47.2‰ to −45.1‰ and a C_1/C_{2+} ratio of 1 to 89 (Fig. 2; including data of Grossman et al., 1986). An approximately 1:1 mixture of migrated thermocatalytic gas (−46‰) and bacterial gas (−65‰) could account for the 10‰ ^{13}C enrichment of Sparta-Queen City methane relative to Yegua-Cook Mountain methane. Substantial input of this gas, however, would lower C_1/C_{2+} ratios in the

TABLE 1. DATA FROM WELLS IN THE YEGUA, COOK MOUNTAIN, SPARTA, QUEEN CITY, AND REKLAW AQUIFERS, EAST-CENTRAL TEXAS

		Ground water			Dissolved gas		Head gas			
Well*	pH	DIC (mmol/l)	$\delta^{13}C_{DIC}$ (‰)	$SO_4^{=}$ (meq/l)	C_1 (µmol/l)	C_2 (µmol/l)	C_1 (mmol/l)⁺	C_2 (µmol/l)⁺	$\delta^{13}C_{C1}$ (‰)	δD_{C1} (‰)
Y78	8.4	7.36	-10.2	2.97	0.52	0.002				
Y100	8.2	12.28	-9.9	0.16	349.60	0.030	9.31	1.16	-61.9	-177
Y134	7.5	14.18	-14.9	0.10	943.80	0.215	15.93	3.93	-71.4	-182
Y260	8.0	4.98	-12.6	1.23	0.23	n.d.§				
Y266	8.1	5.47	-10.1	4.41	0.14	n.d.				
Y276	7.0	3.37	-11.3	3.51	0.72	0.002				
Y295	8.0	4.26	-10.6	2.28	2.50	0.005				
Y300	7.1	3.83	-13.5	1.00	6.06	n.d.				
Y305	7.8	5.59	-11.9	3.43	0.22	n.d.				
Y307	7.8	6.05	-11.6	3.80	0.21	n.d.				
Y315	7.5	5.96	-12.1	5.18	0.25	0.002				
Y324	8.0	5.04	-13.8	0.92	0.34	n.d.				
Y323	8.1	16.85	-10.3	0.00	727.30	n.d.	13.15	0.68	-61.6	-183
Y368	7.7	6.14	-11.1	3.03	0.58	n.d.				
Y390	7.5	3.58	-11.2	0.54	0.14	n.d.				
Y465	8.3	6.39	-10.9	1.53	0.61	0.003				
Y492	8.2	5.65	-12.8	2.59	0.23	n.d.				
Y550	7.6	3.88	-10.9	2.32	0.10	n.d.				
Y1032	7.7	22.44	-2.1	0.08	980.00	n.d.	31.56	3.41	-64.0	-182
CM210	7.5	6.33	-14.1	6.76	2.09	n.d.				
CM250	8.7	9.30	-14.8	0.00	965.10	0.640	13.23	9.95	-67.0	-165
S350	8.7	4.84	-14.3	0.00	1636.40	0.835	29.23	17.29	-54.7	-180
S360	8.1	9.90	-15.4	0.00	1548.80	0.580	31.04	10.26	-56.1	-179
S365	8.3	9.82	-16.6	0.00	1393.60	0.337	29.56	6.11	-55.9	--
S400	8.1	11.59	-12.2	0.00	1252.40	0.487	30.17	14.64	-53.1	-183
S462	8.2	17.20	-5.3	0.00	1413.00	0.370	33.38	7.01	-52.8	-184
S472	8.1	9.67	-19.7	2.57	0.13	0.006	Present		-57.1	--
S492	8.1	12.29	-14.4	1.91	1324.00	0.149	28.80	1.92	-53.7	--
S500	8.5	14.22	-7.8	0.00	1733.00	0.213	28.83	5.58	-55.0	-186
S538	8.7	3.99	-12.2	0.02	1705.20	0.799	29.58	16.86	-54.2	-180
S1560	8.9	10.41	-12.2	4.86	--	--				
Q280	5.5	3.82	-20.0	0.93	4.37	0.002				
Q360	7.5	2.65	-18.3	0.67	0.13	n.d.				
Q380	7.3	4.32	-14.8	1.26	0.13	n.d.				
Q560	8.4	4.32	-13.1	1.95	0.40	n.d.				
Q561	7.6	3.13	-14.5	0.80	0.16	n.d.				
Q569	8.3	3.10	-15.3	0.89	0.21	0.002				
Q572	7.9	4.71	-11.6	2.50	0.56	n.d.				
Q600	8.1	2.91	-15.3	0.93	1.26	n.d.				
Q700	8.6	8.36	-5.4	0.74	0.84	n.d.				
Q784	7.9	3.91	-13.1	0.78	0.14	n.d.				
Q1912	8.2	23.33	-7.8	0.00	706.20	n.d.	Present			
Q1920	8.3	16.80	-9.2	0.05	1229.00	0.120	27.19	5.57	-58.4	-185
Q2000	8.4	15.74	-13.1	1.31	0.49	0.066				
R770	8.4	23.04	0.3	0.00	1346.10	0.410	27.68	1.73	-64.6	-192

*Y = Yegua, CM = Cook Mountain, S = Sparta, Q = Queen City, R = Reklaw; number = well depth in feet.

⁺per liter of head gas.

§n.d. = not detected.

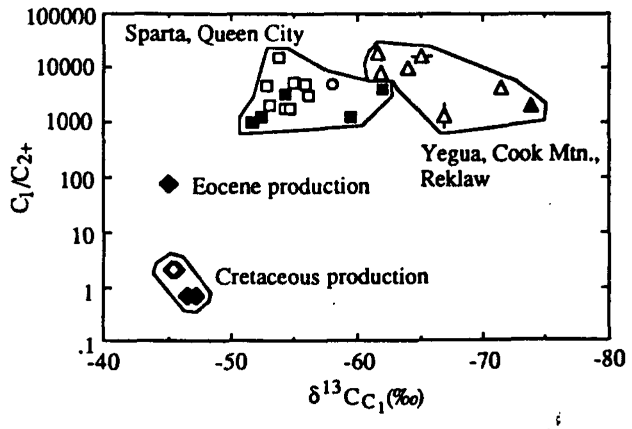


Figure 2. C_1/C_2+ ratios of gaseous hydrocarbons vs. $\delta^{13}C$ of methane for head gas from water wells (same symbols as in Fig. 3) and for gas from hydrocarbon production wells (diamonds). Open symbols—this study; solid symbols—Grossman et al. (1986).

ground-water gaseous hydrocarbons to below 1000 unless migration stripped away most of the C_{2+} component. Migration is the likely cause of the relatively high C_1/C_{2+} ratio of 89 for Eocene production gas. On the basis of its ^{13}C composition, this gas probably migrated from Cretaceous reservoirs where gas has a C_1/C_{2+} ratio of 1 to 2. There is no evidence, however, that this gas migrates into the aquifer at the depths sampled.

Either oxidation of Sparta methane or differences in methanogenic pathway could cause $\delta^{13}C_{C1}$ differences between aquifer methanes. These mechanisms can be tested with hydrogen isotope data. Methane oxidation will enrich residual methane in deuterium as well as ^{13}C (Coleman et al., 1981); methane produced by acetate dissimilation will be greatly depleted in deuterium compared with methane produced by CO_2 reduction (Whiticar et al., 1986). The average δD values of Yegua and Sparta methane are $-181 \pm 3‰$ and $-182 \pm 3‰$, respectively (Table 1). The δD of the water associated with these gases averages $-26 \pm 2‰$. The similar δD values for methane from the two aquifers argues for little or no oxidation of Sparta methane. The relatively high δD values for the methane, compared with values of $< -250‰$ for methane attributed to acetate dissimilation (Whiticar et al., 1986), suggest that methane in both aquifers is produced by CO_2 reduction.

Carbon isotopic measurements of sedimentary organic matter were made to address the possibility that $\delta^{13}C$ differences in methane result from $\delta^{13}C$ differences in available organic carbon. Three thin seams of Yegua lignite had ^{13}C compositions averaging $-26.9 \pm 0.8‰$. Two samples of Sparta black shale had $\delta^{13}C$ values of $-19.8‰$ and $-18.4‰$. This isotopic difference between the Yegua and Sparta sedimentary organic matter ($-7.8‰$) can explain the isotopic difference between methanes from the two aquifers.

Ground-Water Chemistry and the Effect of Methanogenesis

Recharge waters of the Sparta and Queen City aquifers are calcium-sodium-bicarbonate waters. These evolve into sodium-bicarbonate waters as cation exchange progresses (Grossman et al., 1986). Both calcium-sodium-bicarbonate and sodium-bicarbonate waters are low in bicarbonate. The upper limit for this "low-bicarbonate water" is herein set at 7.5 meq/l ($\approx$7.5 mmol/l DIC) based on ^{13}C trends. Further organic matter degradation, combined with calcium carbonate dissolution and cation exchange, causes the high bicarbonate and sodium contents of high-sodium-bicarbonate water (Foster, 1950; Fogg and Kreitler, 1982). This water has bicarbonate contents from about 9 meq/l to greater than 22 meq/l and is herein referred to as "high-bicarbonate water."

For methanogenesis to be pervasive, sulfate concentrations must be low (e.g., Claypool and Kaplan, 1974). In the aquifers studied, dissolved sulfate concentrations range from 0.0 to 6.8 meq/l and have an inverse relation to dissolved methane concentration. Where head gas and abundant dissolved methane (>10 μmol/l) are present, sulfate concentrations are almost always negligible (<0.2 meq/l; Table 1). Thus, conditions in methane-bearing waters are favorable for methanogenesis. However, leakage of methane into an aquifer will enhance sulfate reduction and also result in an inverse relation between sulfate and methane (Kelly et al., 1985).

Ground-water methane and methanogenesis are closely linked to the DIC reservoir and its isotopic composition. As discussed earlier, bacterial breakdown of organic matter along either methanogenic pathway, acetate dissimilation or CO_2 reduction, can result in an increase in the concentration and $\delta^{13}C$ value of ground-water DIC (Games and Hayes, 1976; LaZerte, 1981). The DIC contributed by acetate dissimilation is derived from the acetate's carboxyl group. Limited data suggest that this carbon is about 15‰ enriched in ^{13}C relative to sedimentary organic matter (Blair et al., 1987). In the aquifers of interest, inorganic carbon derived from this source should have a ^{13}C composition between $-15‰$ and $-5‰$. CO_2 reduction succeeds fermentation and/or anaerobic oxidation reactions which produce CO_2 and H_2. Approximately half the CO_2 produced by these reactions is subsequently reduced to CH_4; the remaining CO_2 is added to the DIC in the ground water. Because the CO_2-CH_4 ^{13}C fractionation associated with CO_2 reduction is large, varying in nature from 40‰ to 90‰ (Games and Hayes, 1976; Whiticar et al., 1986), this added DIC can have $\delta^{13}C$ values as high as 20‰.

The $\delta^{13}C_{DIC}$ values of the waters from the east-central Texas aquifers vary from $-20.9‰$ to $+0.3‰$ and reflect the evolution of the ground water (Table 1). This evolution is readily apparent on the $\delta^{13}C_{DIC}$ vs. DIC^{-1} plot (Fig. 3). On such a plot, a mixing curve of two components appears as a straight line, the y-intercept of which equals the $\delta^{13}C$ of the DIC being added.

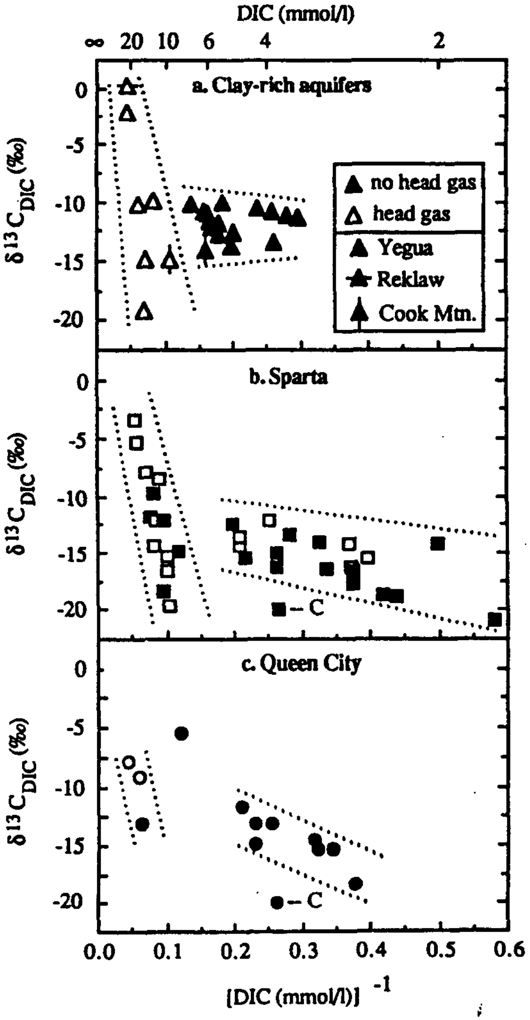


Figure 3. $\delta^{13}C$ of DIC vs. DIC^{-1} for (a) clay-rich aquifers, (b) Sparta aquifer, and (c) Queen City aquifer (including data from Grossman et al., 1986). Dotted lines delineate data for high-bicarbonate water (left) and low-bicarbonate water (right). Open symbols—head-gas bearing; solid symbols—no head gas. Letter C identifies two shallow wells suspected of anthropogenic contamination on basis of excess chloride relative to sodium.

In all aquifers the isotopic trends of low- and high-bicarbonate waters are distinctly different (Fig. 3). Neither trend shows evidence for oxidation of the ^{13}C-depleted methane which occurs in the aquifers. Low-bicarbonate waters show a gentle slope on the $\delta^{13}C_{DIC}$ vs. DIC^{-1} plot, with y intersects suggesting input of DIC with $\delta^{13}C$ values between −12‰ and −7‰. The likely source of this carbon is a combination of dissolution of ^{13}C-depleted soil gas CO_2 (≈−20‰; Reardon et al., 1979), oxidation of organic matter by sulfate reduction (≈−25‰), and carbonate dissolution (≈0‰).

The $\delta^{13}C_{DIC}$–DIC^{-1} trend for high-bicarbonate waters exhibits a steeper slope (Fig. 3). Carbon isotopic compositions "begin" at about −20‰, and increase to about 0‰ with increasing DIC. The Sparta is the only aquifer where we have enough analyses of high-bicarbonate water to demonstrate a statistically significant correlation between $\delta^{13}C_{DIC}$ and DIC^{-1}. Regression of these data yields a y-intercept value, representing the $\delta^{13}C$ of added DIC, of 10‰ (Fig. 3b). Half of the carbon added may be from calcium carbonate dissolution ($\delta^{13}C$ ≈ 0‰). If so, the $\delta^{13}C$ of the DIC added to Sparta water is closer to 20‰. Addition of DIC with $\delta^{13}C$ values of 10‰ or greater is strong evidence for methanogenesis by CO_2 reduction, and evidence that this reaction, along with CO_2-producing fermentation and anaerobic oxidation reactions, is responsible for high bicarbonate content in Sparta waters.

The same processes control the chemistry of the high-bicarbonate waters from the Queen City and Yegua aquifers. Although fewer data are available for these aquifers, high-bicarbonate waters show $\delta^{13}C_{DIC}$–DIC^{-1} trends suggestive of input of ^{13}C-enriched DIC (Fig. 3, a and c). It is likely that this process is responsible for high-bicarbonate waters in other Gulf Coast aquifers as well.

If methanogenesis is important in the formation of high-bicarbonate waters, then these waters should be methane-bearing and low-bicarbonate waters should be methane-free. Of 70 wells shown in Figure 3, there are only 12 exceptions. Six low-bicarbonate waters in the Sparta have significant methane, and six high-bicarbonate waters in the Sparta and Queen City are essentially methane-free. These exceptions may result from migration of methane or mixing of waters within the aquifer. Two Sparta wells bearing methane in low-bicarbonate water (wells H and I reported in Grossman et al., 1986) are city wells with large cones of depression which may enhance either of these processes.

CONCLUSIONS

Bacterial production of methane predominantly by CO_2 reduction is responsible for the occurrence of methane in Eocene aquifers in east-central Texas. CO_2 produced by fermentation and anaerobic oxidation reactions occurring in conjunction with methanogenesis is responsible for high bicarbonate contents in these ground waters. Methane from the Yegua-Cook Mountain and Sparta-Queen City aquifer systems differ in average $\delta^{13}C$ by 10‰. This corresponds to an 8‰ difference in the $\delta^{13}C$ of sedimentary organic matter from the Yegua and Sparta Formations. Combined with hydrogen isotope data, this observation suggests that the difference in methane $\delta^{13}C$ values between aquifers is caused by substrate differences, not by input of thermocatalytic gas or differences in methanogenic pathway.

REFERENCES CITED

Barker, J.F., and Fritz, P., 1981, The occurrence and origin of methane in some groundwater flow systems: Canadian Journal of Earth Sciences, v. 18, p. 1802–1816.

Bernard, B., Brooks, J.M., and Sackett, W.M., 1977, A geochemical model for characterization of hydrocarbon gas sources in marine sediments: Houston, Texas, Offshore Technology Conference, 9th, Proceedings, p. 435–438.

Blair, N.E., Martens, C.S., and Des Marais, D.J., 1987, Natural abundances of carbon isotopes in acetate from a coastal marine sediment: Science, v. 236, p. 66–68.

Chapelle, F.H., and Knobel, L.L., 1985, Stable carbon isotopes of HCO_3^- in the Aquia aquifer, Maryland: Evidence for an isotopically heavy source of CO_2: Ground Water, v. 23, p. 592–599.

Chapelle, F.H., Zelibor, J.L., Jr., Grimes, D.J., and Knobel, L.L., 1987, Bacteria in deep coastal plain sediments of Maryland: A possible source of CO_2 to groundwater: Water Resources Research, v. 23, p. 1625–1632.

Chapelle, F.H., Morris, J.T., McMahon, P.B., and Zelibor, J.L., Jr., 1988, Bacterial metabolism and the $\delta^{13}C$ composition of ground water, Floridan aquifer system, South Carolina: Geology, v. 16, p. 117–121.

Claypool, G.E., and Kaplan, I.R., 1974, The origin and distribution of methane in marine sediments, *in* Kaplan, I.R., ed., Natural gases in marine sediments: New York, Plenum Press, p. 99–139.

Coleman, D.D., 1976, Isotopic characterization of Illinois natural gas [Ph.D. thesis]: Urbana-Champaign, University of Illinois, 175 p.

Coleman, D.D., Meents, W.F., Liu, C-L., and Keogh, R.A., 1977, Isotopic identification of leakage gas from underground storage reservoirs—A progress report: Illinois Geological Survey, Illinois Petroleum 111, 10 p.

Coleman, D.D., Risatti, J.B., and Schoell, M., 1981, Fractionation of carbon and hydrogen isotopes by methane-oxidizing bacteria: Geochimica et Cosmochimica Acta, v. 45, p. 1033–1037.

Coleman, M.L., Shepherd, T.J., Durham, J.J., Rouse, J.E., and Moore, G.R., 1982, Reduction of water with zinc for hydrogen isotope analysis: Analytical Chemistry, v. 54, p. 993–995.

Fogg, G.E., and Kreitler, C.W., 1982, Ground-water hydraulics and hydrochemical facies in Eocene aquifers of the east Texas basin: Texas Bureau of Economic Geology Report of Investigations no. 127, 75 p.

Follett, C.R., 1974, Ground-water resources of Brazos and Burleson counties: Texas Water Development Board Report 185, 193 p.

Foster, M.D., 1950, The origin of high sodium bicarbonate waters in the Atlantic and Gulf coastal plains: Geochimica et Cosmochimica Acta, v. 1, p. 33–48.

Fuex, A.N., 1980, Experimental evidence against an appreciable isotopic fractionation of methane during migration: Progress in Physics & Chemistry of the Earth, v. 12, p. 725–732.

Games, L.M., and Hayes, J.M., 1976, On the mechanisms of CO_2 and CH_4 production in natural anaerobic environments, *in* Nriagu, J.O., ed., Environmental biogeochemistry, Volume 1: Ann Arbor, Michigan, Ann Arbor Science, p. 51–73.

Grossman, E.L., Hahn, R.W., and Fritz, S.J., 1986, Origin of gaseous hydrocarbons in the Sparta aquifer in Brazos and Burleson counties, Texas: Gulf Coast Association of Geological Societies Transactions, v. 36, p. 458–470.

Kelly, W.R., Matisoff, G., and Fisher, J.B., 1985, The effects of gas well blow out on groundwater chemistry: Environmental Geology and Water Sciences, v. 7, p. 205–217.

Klass, D.L., 1984, Methane from anaerobic fermentation: Science, v. 223, p. 1021–1028.

LaZerte, B.D., 1981, The relationship between total dissolved carbon dioxide and its stable carbon isotope ratio in aquatic sediments: Geochimica et Cosmochimica Acta, v. 45, p. 647–656.

McAuliffe, C., 1966, Solubility in water of paraffin, cycloparaffin, olefin, acetylene, cycloolefin, and aromatic hydrocarbons: Journal of Physical Chemistry, v. 70, p. 1267–1275.

Reardon, E.J., Allison, G.B., and Fritz, P.; 1979, Seasonal chemical and isotopic variations of soil CO_2 at Trout Creek, Ontario, *in* Back, W., and Stephenson, D.A., eds., Contemporary hydrogeology—The George Burke Maxey memorial volume: Journal of Hydrology, v. 43, p. 355–371.

Schoell, M., 1983, Genetic characterization of natural gases: American Association of Petroleum Geologists Bulletin, v. 67, p. 2225–2238.

Sellards, E.H., Adkins, W.S., and Plummer, R.B., 1932, The geology of Texas, Volume 1, Stratigraphy: University of Texas Bulletin 3232, 1007 p.

Stahl, W., 1974, Carbon isotope fractionations in natural gases: Nature, v. 251, p. 134–135.

Whiticar, M.J., Faber, E., and Schoell, M., 1986, Biogenic methane formation in marine and freshwater environments: CO_2 reduction vs. acetate fermentation—Isotope evidence: Geochimica et Cosmochimica Acta, v. 50, p. 693–709.

Wolin, M.J., and Miller, T.L., 1987, Bioconversion of organic carbon to CH_4 and CO_2: Geomicrobiology Journal, v. 5, p. 239–259.

ACKNOWLEDGMENTS

This study was supported by Center for Energy and Mineral Resources and Water Resources Research Enhancement grants, Texas A&M University. We thank J. M. Brooks for access to the facilities of the Geochemical and Environmental Research Group; R. Pflaum, J. Alcala-Herrera, and T. McDonald for assistance with analyses of gaseous hydrocarbons and lignite; Robert Hahn for assistance with initial sampling; the city of Deanville and private well owners for allowing access to wells; and Frank Chapelle, George Claypool, Dennis Coleman, and Lisa Pratt for careful reviews of the manuscript.

Manuscript received July 29, 1988
Revised manuscript received February 1, 1989
Manuscript accepted February 7, 1989