Sources of Salt-Water Pollution

in

Western Tom Green County

by

Bernd C. Richter, Alan R. Dutton, and Charles W. Kreitler

Prepared for the
Railroad Commission of Texas
Austin, Texas
under contract no. IAC (86-87)-1003

Bureau of Economic Geology
W. L. Fisher, Director
The University of Texas at Austin
Austin, Texas 78713-7508

July 1987

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ABSTRACT

Tom Green County lies in the discharge zone of the Permian Basin regional flow system in West Texas. Hydrochemical facies and ionic ratios of major chemical constituents indicate that much of the saline ground water in the area is a mixture of subsurface brine flowing eastward from the Permian Basin and locally recharged, shallowly circulating meteoric water. Aquifers that contain relatively fresh water in outcropping Paleozoic rocks contain brine and hydrocarbons as shallow as 200 to 900 ft (60 to 270 m) just tens of miles to the west. Chemical composition of ground water is strongly associated with the outcrop of Paleozoic formations from which brine is discharged.

Three major mechanisms for mixing of subsurface brine and shallow ground water could be documented by test drilling but is not reflected in the chemical composition of the mixtures because of the chemical similarity between natural brine in shallow units and brine that flows into the shallow subsurface from the deeper Coleman Junction Formation via insufficiently plugged holes. (1) The presence of brine and thus of natural discharge at shallow depth below the base of fresh water in the Permian San Angelo Formation of central Tom Green County was proven by test drilling. (2) Abandoned exploration holes allow upward flow of brine where depths of surface casing and plugs are less than the base of fresh water. Seepage of brine from the overpressured Coleman Junction Formation into the shallow subsurface was observed in one hole and is suggested by test drilling in another. (3) Leaching of salt from soil underlying former brine-disposal sites is an ongoing process even 20 years after discontinuation of the brine disposal-method. Water samples collected during drilling into former pits were highly

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saline. The presence of a fourth mixing mechanism of brine and shallow ground water via abandoned water wells could not be proven. No records exist on deep water wells that were drilled into saline portions of aquifers and that were abandoned without plugging.

Geochemical differentiation between shallow subsurface brine and brine from deep Pennsylvanian reservoirs as well as identification of mixing between shallow ground water and the shallow brine system was made possible by (1) using bivariate plots of Ca, Mg, Na, and SO_4 concentrations and of Br/Cl ratios versus chloride concentrations, (2) using bivariate plots of Cl/SO_4 ratios versus SO_4 concentrations and versus Na/Ca ratios, and (3) determining anomalous hydrochemical facies. Organic acids, isotopes of hydrogen, oxygen, carbon, and sulfur, and minor and trace constituents other than bromide did not provide significant information in this study.

INTRODUCTION

Saline to brackish ground water is found in many water wells in the Concho River valley of West Texas. Richter and Kreitler (1985) determined that poor-quality water in Tom Green, Runnels, and Concho Counties (fig. 1) might be due to natural discharge of subsurface brines, upward movement of brine across confining beds through unplugged water wells and oil wells into aquifers, seepage of saline water from rocks beneath former brine-disposal pits, and evaporative concentration of ground water from shallow water tables that have risen in response to changed agricultural landscaping and increased recharge. Many ground-water samples having high salinity from western Tom Green County appeared to be influenced by mixing of fresh water and subsurface brine. A common concern

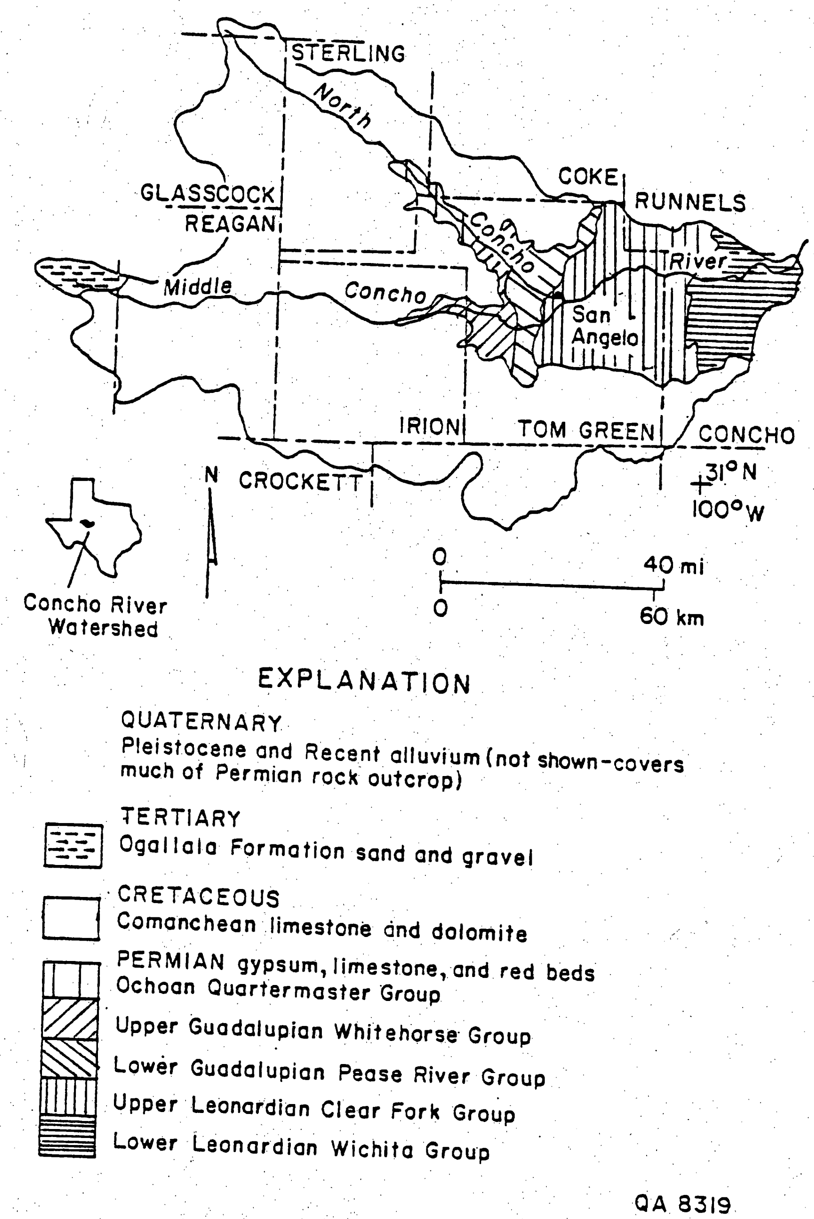

Figure 1. Simplified geologic map of Concho River watershed (modified from American Association of Petroleum Geologists, 1973).

is that recent changes in ground-water salinity might be due to oil field activities, such as seepage from abandoned brine-disposal pits and from oil wells with leaky casings.

This investigation was designed to characterize chemical variations in fresh ground waters and subsurface brines in Tom Green and eastern Irion Counties, Texas, to characterize ground water associated with possible sources of saline water, and to develop diagnostic hydrochemical tools to recognize and locate sources of saline ground water in shallow aquifers. Regional and local hydrogeologic controls on natural occurrence of saline water in the study area must be understood to establish a baseline for documenting anthropogenic salinity effects. Salinity and hydrochemical facies distributions in shallow ground waters are examined, chemical variations among subsurface brines are discussed, and chemical similarities between shallow ground waters and subsurface brines are indicated. We use the term "shallow ground water" to refer to potable water supplies in aquifers at depths of less than about 400 ft (120 m). "Subsurface brine" refers to water of high salinity typically associated with oil fields and commonly occurring at depths of greater than 1,000 ft (300 m).

Hydrogeologic Setting

The study area in Tom Green and eastern Irion Counties (fig. 1) is at the eastern edge of the Southern Great Plains physiographic province. The Southern Great Plains is inclined to the southeast from altitudes of 6,000 to 8,000 ft (1,800 to 2,400 m) in eastern New Mexico to altitudes of 1,500 to 2,000 ft (450 to 600 m) in Central Texas. Physiography of the study area includes flat alluvium-floored valleys, formed by the Concho River and its tributaries, separated from the gently rolling, dissected upland of the Edwards Plateau by an escarpment with a maximum height of approximately 100 ft (30 m).

Cretaceous carbonate rocks that underlie the Edwards Plateau in the study area unconformably overlie Permian sandstone, carbonate rock, and shale, which were deposited on the eastern shelf of the Midland Basin and which dip to the west. The Comanche Peak limestone of the Fredericksburg Group and the Antlers sandstone of the Trinity Group form two interconnected aquifers in Cretaceous rock. Potable ground waters also are produced from aquifers in the Permian Clear Fork and Pease River Groups (table 1); the Permian groups in many areas of the Concho River valley are covered by Pleistocene and Quaternary alluvium (Willis, 1954; Lee, 1986).

Drilling for and production of oil started in the area in the early 1900's. Oil and oil shows were originally encountered at depths as shallow as 43 ft (13 m) below land surface (Udden and Phillips, 1911). At present, oil and gas is produced from Paleozoic rocks at depths ranging from as shallow as 900 ft (270 m) in Permian formations to greater than 6,000 ft (1,800 m) in Ordovician rocks. Subsurface brine is prevalent throughout the Paleozoic section at varying depth below land surface. Seepage of salt water from this section at land surface is widespread but not just a recent phenomenon. The occurrence of salt water at and near land surface was reported as early as 1911 (Udden and Phillips, 1911). Upper Permian rocks that compose fresh-water aquifers beneath the Concho River valley contain brine and hydrocarbons just tens of miles west of the study area in the subsurface (McNeal, 1965; Core Laboratories, 1972). For example, figure 2 shows that salinity of subsurface water in the Upper Permian San Andres (Blaine)

Table 1. Generalized stratigraphic chart for Tom Green and eastern Irion Counties.

System	Series	Group	Formation	Lithology
Quaternary	Holocene			alluvium
	Pleistocene		Leona	caliche and gravel
Cretaceous	Comanchean	Washita	Buda	argillaceous limestone
		Fredericksburg	Edwards	limestone and dolomite
			Comanche Peak	limestone
			Walnut	marl and clay
		Trinity	Antlers	sandstone and shale
Upper Triassic		Dockum	undifferentiated	sandstone and shale
Permian	Ochoan	Quartermaster	undifferentiated	sandstone and gypsiferous shale
	Guadalupian	Whitehorse	undifferentiated	sandstone and gypsiferous shale
		Pease River	San Andres (Blaine)	sandstone
			San Angelo	sandstone, gypsum, and dolomite
	Leonardian	Clear Fork	Choza	shale and dolomitic limestone
			Vale	shale and dolomitic limestone
			Arroyo	shale and marly limestone
		Wichita-Albany	Leuders	limestone and dolomite
			Talpa	limestone and shale
			Grape Creek	
			Bead Mountain	
			Jagger Bend-Valera	
			Elm Creek	
	Wolfcampian		Admiral	
			Coleman Junction	
		Cisco	undifferentiated	limestone and shale
Pennsylvanian	Virgilian			
	Missourian	Canyon		limestone
	Desmoinesian	Strawn		limestone and shale
	Atokan	Bend		sandstone, shale, and limestone
	Morrowan			
Lower Ordovician		Ellenburger	"Ellenburger"	dolomite

Modified from Barnes (1972, 1974), American Association of Petroleum Geologists (1973), and Lee (1986)

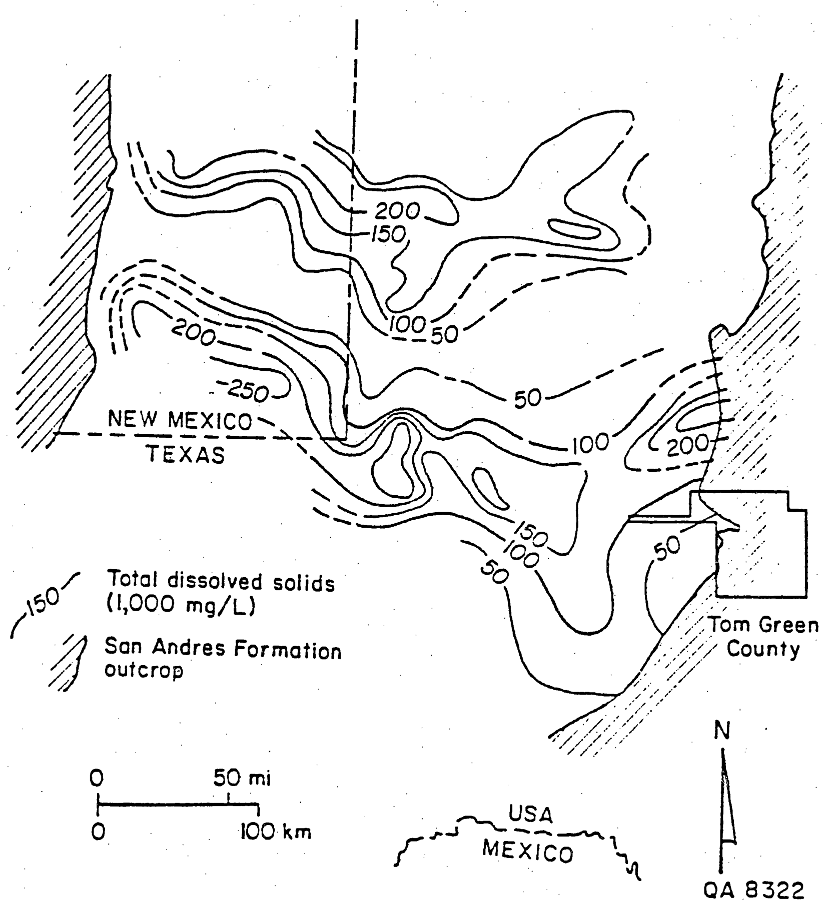

Figure 2. Total dissolved solids in formation water from the San Andres Formation (modified from McNeal [1965]).

Formation varies from 50,000 mg/L in eastern Irion County to more than 200,000 mg/L in the Midland Basin to the west.

The influence of regional and local topographic relief on ground-water flow paths (Toth, 1978) must be understood to distinguish correctly between naturally occurring saline waters and salt-water contamination in Tom Green and eastern Irion Counties. Regional topographic relief across the Southern Great Plains imposes a hydrodynamic gradient on subsurface brine in Paleozoic rocks (McNeal, 1965; Dutton and Orr, 1986; Wirojanagud and others, 1986). Potentiometric surfaces of subsurface brines are inclined toward the east, indicating potential for eastward fluid flow toward formation outcrops (fig. 3). Eastward flow of subsurface water across the Eastern Shelf probably influenced migration of hydrocarbons into reservoirs. The eastward flow during the past several million years also has probably transported subsurface brine to near land surface, where the brine mixes with locally recharged, shallowly circulating water. Richter and Kreitler (1986) showed that brine at shallow (100 ft [30 m]) depths in the southern part of the Rolling Plains northwest of the study area are derived from deep parts of the Permian Basin. Comparison of potentiometric surfaces of hydrostratigraphic units in Paleozoic rocks mapped by McNeal (1965) in Tom Green and eastern Irion Counties indicates that there is potential for movement of subsurface brine upward across confining layers toward discharge sites if pathways exist, such as through fractures and unplugged boreholes. Potentiometric surfaces of subsurface brines in the study area generally are close to land surface in the Concho River valley. This is consistent with observations that brine in the Permian Coleman Junction Formation (table 1), at approximate depths of 1,500 ft (450 m) just east of Tom Green County to 3,000 ft (900 m) in eastern Irion County, rises to near or

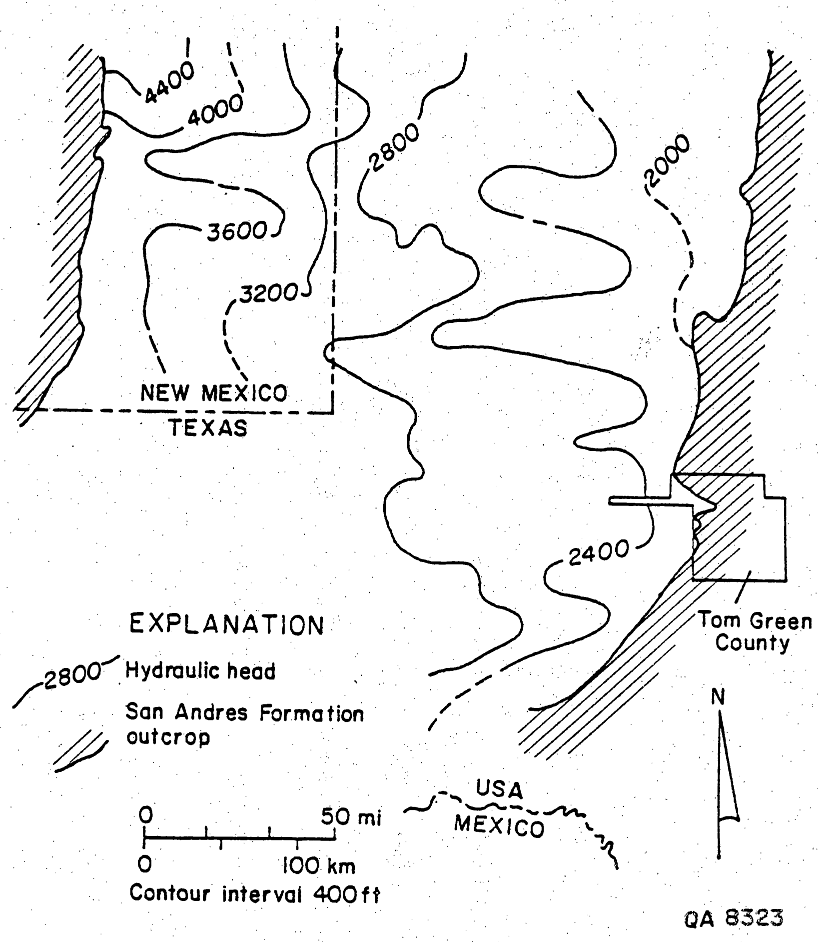

Figure 3. Potentiometric surface of the San Andres Formation based on equivalent fresh-water hydraulic head (modified from McNeal [1965]).

somewhat above land surface in old well bores (Richter and Kreitler, 1985).

Potentiometric surfaces of shallow aquifer units are inclined towards the Concho River and its tributaries (Lee, 1986), reflecting topographic control on flow directions of shallow ground water. Lee (1986) reported that hydraulic head of ground water increases downward from land surface beneath the Concho River and decreases downward beneath the floodplains and plateaus adjacent to the river. This pattern indicates that the rocks of the Edwards Plateau are local recharge areas and that ground-water discharge occurs primarily in the valleys of the Concho River and its tributaries. Subsurface brine in the Southern Great Plains regional ground-water flow system also probably discharges at low elevations in the Concho River valley, influencing ground-water quality in surface-water bodies and fresh-water aquifers.

Methods and Data

In this study, we used data on the chemical composition of subsurface brine collected at oil wells and shallow ground water at existing water wells and specially drilled test wells as well as existing chemical data compiled from reports and computer files. To document local variation and hydrogeologic controls on ground-water quality, chemical analyses and production-zone elevations of 646 samples of ground water in Tom Green and eastern Irion Counties (app. 1) were compiled from Work Projects Administration (1941), Willis (1954), Pool (1972), Richter and Kreitler (1985), Lee (1986), and computerized and open-file records of the Texas Natural Resources Information System. Well locations were digitized with Universal Transverse Mercator (UTM) coordinates from base maps.

Reported analyses of the chemical composition of ground water vary in completeness and in conditions of sample treatment. Temperature, pH, and alkalinity were not always measured on site and therefore are unreliable measurements of in situ values; pH commonly is not reported (app. 1). The charge balance of anions and cations is almost always exact, indicating that sodium and potassium were determined together by calculating the difference (Hem, 1985, p. 164).

Seventeen subsurface brines were collected during two weeks in May and June 1986 to establish whether chemical composition of water differs in oil and gas fields in Tom Green and eastern Irion Counties (fig. 4) and whether diagnostic tracers of formation-specific brines could be identified. Brines from the same formation were taken from different fields, but only one sample was collected at each field. Care was taken to avoid sampling wells where natural subsurface brine may have been contaminated by injected salt water. Files at the Central Records Office and at the San Angelo District Office of the Railroad Commission of Texas were reviewed to locate wells used for salt-water injection for disposal or for secondary oil recovery between 1965 and early 1986. All fields that produce oil from the San Andres and San Angelo Formations in the study area contain some salt-water-injection wells. To collect ground-water brine that is representative of these formations, wells as far as possible from injection wells were sampled.

Shallow ground-water samples were collected during April and May 1987. A commercial analytic laboratory in San Angelo, Texas, provided recent chemical analyses of ground water that formed the basis of a sampling program for shallow saline ground waters. Of more than 1,000 samples that were analyzed between 1977 and 1987, 30 samples with chloride concentrations greater than 2,000 mg/L

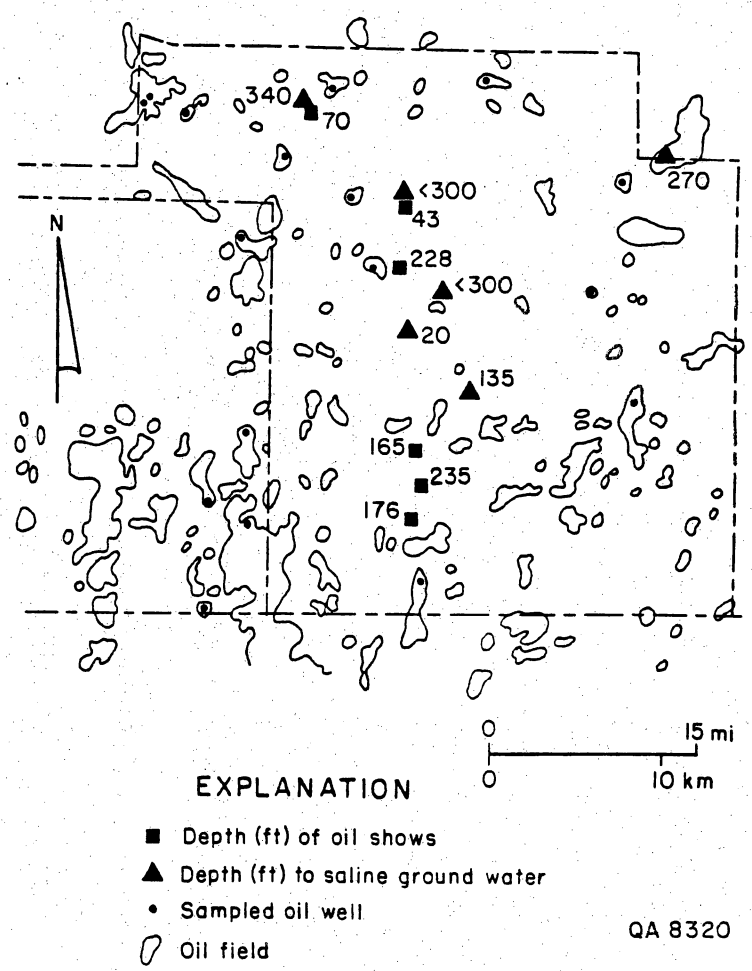

Figure 4. Oil and gas fields in Tom Green and eastern Irion Counties. Also shown is early evidence of shallow oil and salt water (Udden and Phillips, 1911).

were identified. Nine of these 30 sites were resampled. Another four samples were obtained from water wells where salinity reportedly had increased.

Six test holes were drilled by air-rotary method for collection of shallow ground-water samples from below the base of fresh water. Test holes were drilled at sites where salt water had been previously encountered by the land owners during water-well drilling. After samples were collected, test wells were entirely filled with cement. Eight water samples were obtained from 5 test holes; one test hole was dry. Nonsaline water-bearing units encountered during drilling were sealed after a sample was taken, and then drilling continued. Test holes were also drilled by air-rotary method at three abandoned brine-disposal pits. Soil samples were obtained in 5-ft (1.5-m) and in 10-ft (3-m) intervals during drilling, and water samples were collected from the shallowest water encountered. Soil samples were weighed, stored in preweighed plastic cups with screw-on caps, and kept on ice in the field before chloride concentration and moisture content were determined in the laboratory.

Concentrations of chemical constituents are reported in the tables as milligrams per liter (mg/L) and are plotted in dimensions of mg/L and milliequivalents per liter (meq/L). Dimensions of meq/L are calculated by multiplying molar concentrations of an individual constituent by its valence and are used for control of charge balance of a water analysis (control of accuracy). Conversion factors from mg/L to meq/L are listed in appendix 2.

Drillers' logs and plugging reports for abandoned oil exploration boreholes were used to evaluate pollution hazards of upward-flowing subsurface brines. An abandoned dry hole was selected for test drilling to test the accuracy of plugging reports and to determine effectiveness of plugging. After a permit for reentering and replugging had been obtained from the Railroad Commission of Texas, the surface plug was drilled out, and plug thickness and position were compared with those of the original plugging report. A test hole 150 ft (45 m) down gradient from the hole was drilled to test for brine leakage from the abandoned borehole.

To assess the potential for salt-water pollution from former brine-disposal pits, the amount of subsurface brine disposed in unlined pits in the study area during 1950 to 1969 was estimated by multiplying reported volume of oil production by water/oil ratios for various leases in the study area. Two independent estimates of water/oil ratios were made: one was based on 4 representative years of data reported in Form W-10, Oil Well Status Report of the Railroad Commission of Texas; the other was derived from brine-production data contained in three operator surveys conducted by the Railroad Commission of Texas. Response to the salt-water surveys was voluntary and may be less complete than Form W-10 data. Water/oil ratios were calculated for individual leases from Form W-10 data and then averaged; ratios from salt-water surveys are averages of total water and oil produced (table 2).

Sampling Technique

Similar methods were followed for collection and treatment of both subsurface brine and shallow ground water: methods differed only in the need to remove oil from subsurface brine. The proportion of gas, oil, and water produced from sampled oil wells varied among fields. The water/oil ratio in fluid produced from some fields is high enough that adequate sample volume could be separated from

Table 2. Data used to estimate amount of salt water produced from oil and gas fields in Tom Green and Irion Counties, 1950-1969.

Water/Oil Ratios From W-10 Forms (bbl/bbl)

	1953	1958	1964	1969
arithmetic average	0.94	0.56	0.68	1.37
arithmetic median	0.09	0.07	0.19	0.18
geometric mean	0.05	0.02	0.17	0.18
mean + 1 standard deviation	1.45	0.77	1.62	2.18
mean - 1 standard deviation	0.002	0.001	0.017	0.014
sample size	15	15	22	29

Water/Oil Ratios From Salt-Water Surveys

	1957	1961	1967
brine production (bbl)	3,434	2,285,129	2,397,417
oil production (bbl)[1]	2,576,564	2,208,644	2,908,602
water/oil ratio (bbl/bbl)	0.001	1.035	0.824

Cumulative Oil Production (1,000 bbl)[1]

1953	1958	1964	1969
6,428	17,458	30,726	42,220

Cumulative Brine Production (1,000 bbl)

Water/Oil Estimate	1953	1958	1964	1969
arithmetic average	6,042	9,776	20,893	57,841
arithmetic median	578	1,222	5,838	7,580
geometric mean	321	349	5,223	7,580
mean + 1 standard deviation	9,320	13,443	49,776	92,040
mean - 1 standard deviation	13	17	522	591

[1] From Annual Reports of the Oil and Gas Division, Railroad Commission of Texas.

oil at the wellhead. At other fields with lower water/oil ratios, samples were taken from a separator tank. Sampling followed methods for collection of oil field waters recommended by Lico and others (1982). Oil and water mixtures were collected in a 1-gal bucket with a drum tap inserted in its side. Up to five minutes was generally enough time for oil and water to separate; the water then was drained from the drum tap through a glass-wool-lined funnel into a filter chamber; the glass wool removed any remaining oil. Waters were filtered (A/E-type glass filter or 0.45-μm membrane filter) under N_2-gas pressure to remove suspended solids and particulates. Acid-washed sample bottles were filled from the stream of water leaving the filter.

Temperature was measured in the fluid stream being sampled at the wellhead or separator tank. Alkalinity and pH of some samples were measured at the well site; malfunction of the field pH meter required measurement of alkalinity and pH of nine samples approximately 3 to 8 hours after collection. Standard sample treatment immediately after collection preserved unstable constituents for chemical analysis. Samples for cation analysis were acidified with 5 mL of 6N HCl per 500-mL sample. Fifty mL of ammonical $SrCl_2$ (Gleason, 1969) were added to 1-L sample for precipitation of $SrCO_3$ and analysis of $\delta^{13}C$. Samples for analysis of $\delta^{34}S$ of dissolved sulfate were acidified with 5 mL of 6N HCl per 500-mL sample and 5 mL of 5% Cd-acetate were added to prevent any dissolved sulfide ions from oxidizing to sulfate. Samples for $\delta^{18}O$ and δD were collected in 250-ml glass bottles with screw-on caps. All oil field brines and 10 ground-water samples were analyzed for aliphatic acid (carboxylic acid) anions (acetate, propionate, butyrate, and valerate). These samples were collected in 250-ml polyethylene bottles and treated in the field with several drops of 5% $HgCl_2$ to inhibit biological alteration of organic acids.

RESULTS

Salinity Distribution

Richter and Kreitler (1985) and Lee (1986) recognized that patterns of high chlorinity changed in Tom Green County between the 1940's and 1970's. Distribution of salinity in Tom Green and eastern Irion Counties was reanalyzed in this study to determine if salinity patterns correlate with formation lithology and local physiography. Figures 5 through 7 show that total dissolved solids tends to be less than 500 mg/L in the Cretaceous limestones of the Edwards Plateau (fig. 1) but greater than 1,000 mg/L in Concho River valley alluvium and subcropping Permian formations. There are numerous water samples from wells in the valleys with total dissolved solids of more than 10,000 mg/L. Salinity of ground waters sampled prior to 1942 show a strong stratigraphic association with the outcrop and subcrop of Permian formations, which strike northeast across the study area (figs. 1 and 5). Salinity distribution mapped from water samples collected between 1942 and 1954 (fig. 6) and between 1955 and 1980 (fig. 7) appears to be less strongly controlled by Permian strata. Overall salinity in the Concho River valley appears to have increased from pre-1942 to the early 1950's and then decreased during the 1960's and 1970's. The exact salinity patterns are affected by data availability because different sets of water analyses were used for each map; changes in county-wide salinity distributions might not reflect changes in water quality at any one well.

Hydrochemical Facies

Hydrochemical facies distributions reflect rock type and sample position along ground-water flow paths. Hydrochemical facies are named for the ions that

Prior to 1942

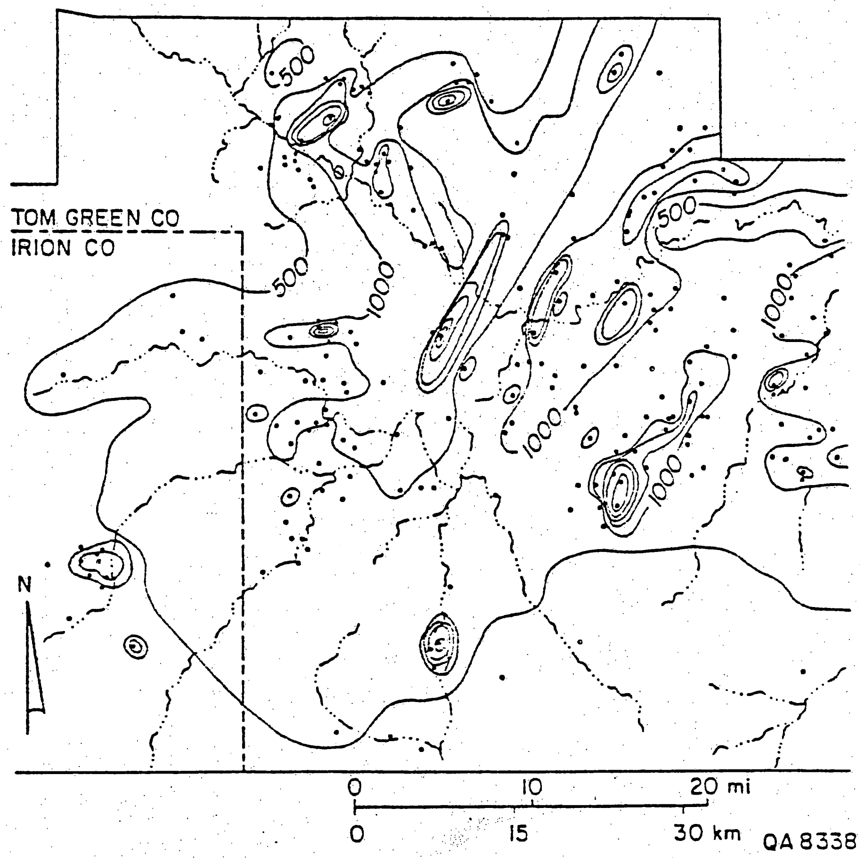

Figure 5. Total dissolved solids in ground water in Tom Green and eastern Irion Counties collected prior to 1942. Variable contour interval (500-1,000-2,000-3,000-10,000-50,000 mg/L).

1942-1954

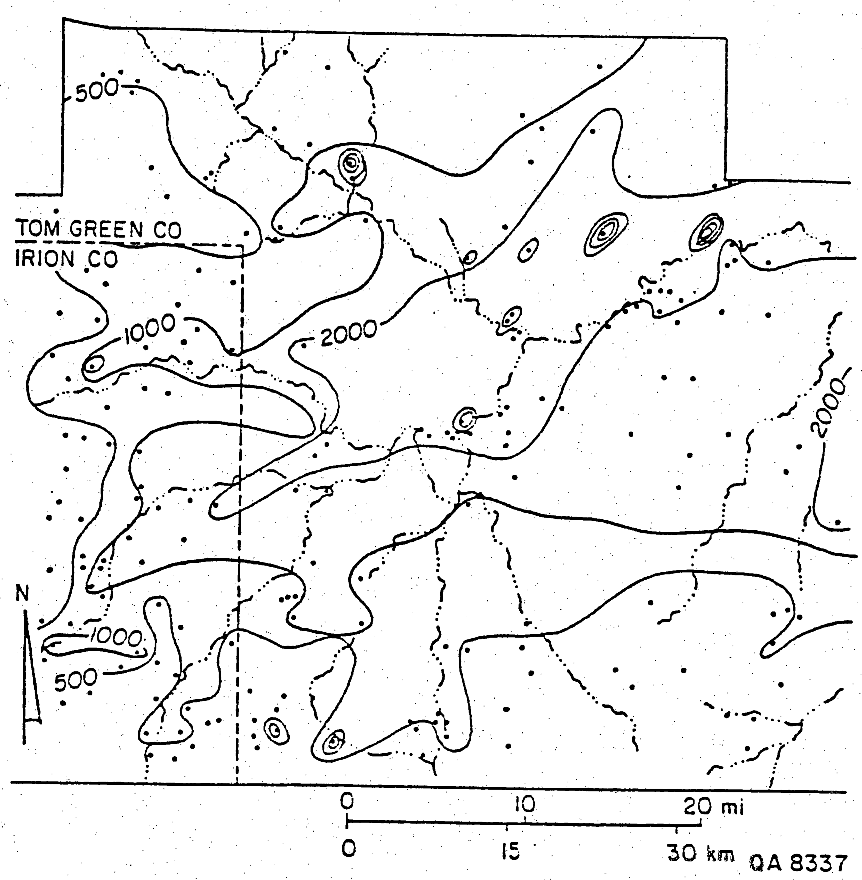

Figure 6. Total dissolved solids in ground water in Tom Green and eastern Irion Counties collected between 1942 and 1954. Variable contour interval (500-1,000-2,000-3,000-10,000-50,000 mg/L).

After 1954

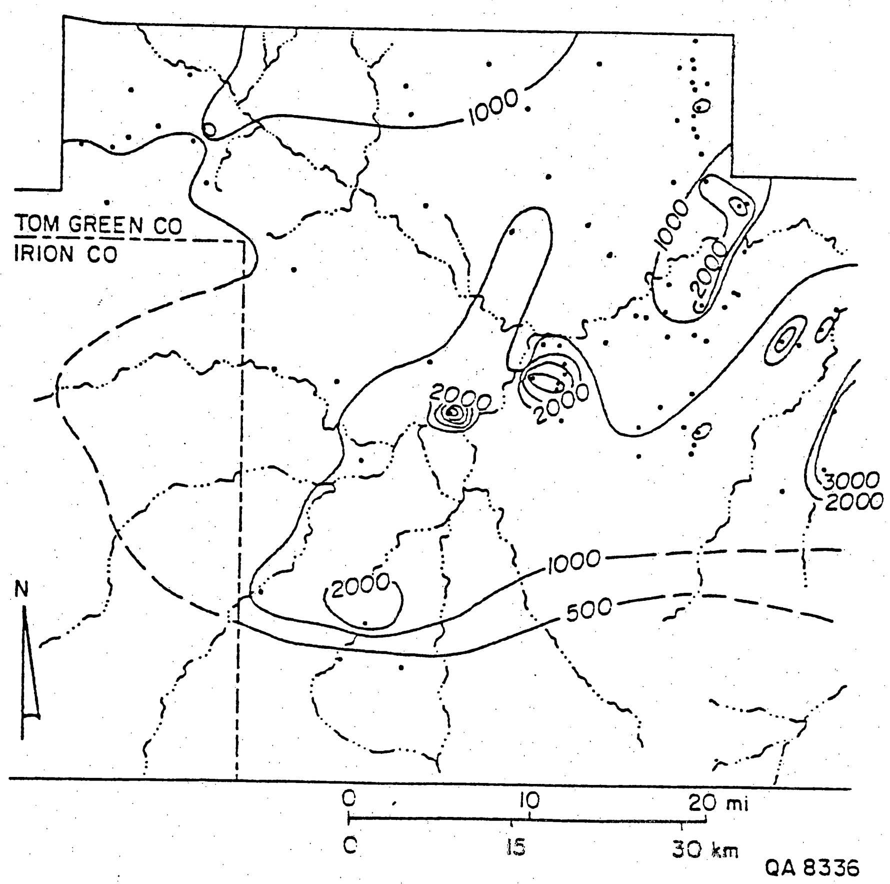

Figure 7. Total dissolved solids in ground water in Tom Green and eastern Irion Counties collected after 1954. Variable contour interval (500-1,000-2,000-3,000-10,000-50,000 mg/L).

account for at least 50 percent of total equivalent concentration as depicted in Piper diagrams (Back, 1966). Mixed-cation and mixed-anion hydrochemical facies are waters in which no one cation or anion is dominant (fig. 8). Major hydrochemical facies in Tom Green and Irion Counties include Ca-HCO_3, Na-HCO_3, and mixed-cation-HCO_3 types in limestones of the Cretaceous Trinity and Fredericksburg Groups; mixed-cation-Cl, mixed-cation-SO_4, and mixed-cation-mixed-anion types in the Pleistocene Leona Formation and other Quaternary carbonate gravels and sands beneath the Concho River valley; and Na-Cl and Ca-SO_4 types in Permian San Angelo, Vale, and Arroyo Formations (table 1) that subcrop beneath Pleistocene alluvium in the Concho River valley (fig. 9). In addition, Na-Cl, Ca-SO_4, Ca-mixed-anion, and Na-mixed-anion hydrochemical facies are locally present in western Tom Green and eastern Irion Counties and are geographically anomalous owing to their position within large areas dominated by other hydrochemical facies (fig. 8).

Chemical Composition of Shallow Waters with High Chlorinity

Richter and Kreitler (1985) stated that sources of salinity can be most readily detected in waters with high total dissolved solids (TDS). Therefore, sampling conducted during this study emphasized waters with relatively high concentrations of TDS.

TDS of specially sampled shallow ground water ranged from 832 to 5,332 mg/L, and chloride ranged from 200 to 2,100 mg/L (table 3). Concentration ranges in these samples do not reflect normal water quality of ground water in Tom Green County but represent the most saline waters found at existing water wells. In contrast, samples from previous water-resource

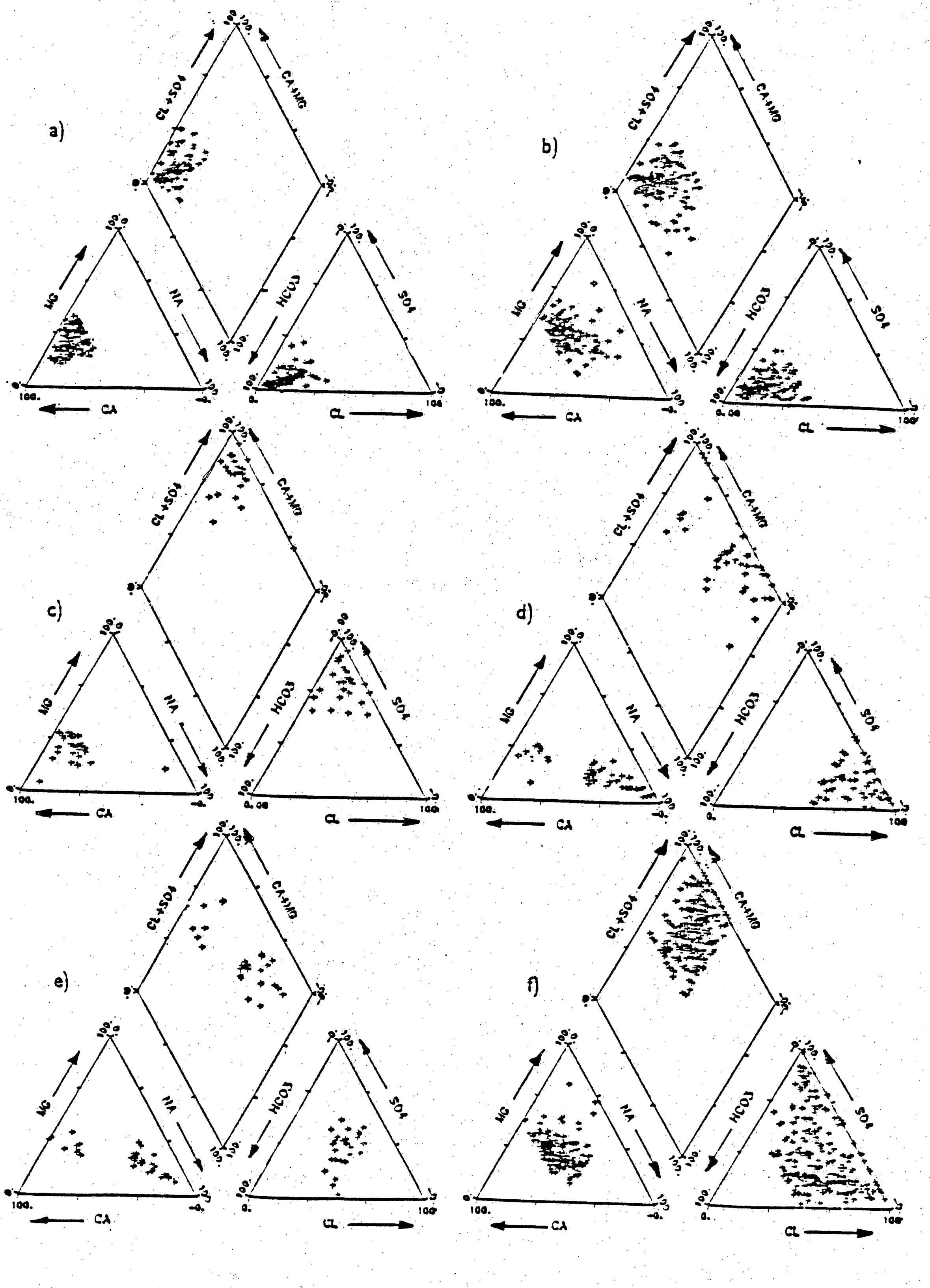

Figure 8. Piper diagrams of hydrochemical facies in shallow aquifers in Tom Green and eastern Tom Green County. (a) Ca-HCO_3. (b) Na-, Mg-, and mixed-cation-HCO_3. (c) Ca-SO_4. (d) Na-Cl and Ca-Cl. (e) Ca- and Na-mixed-anion. (f) Mg- and mixed-cation-mixed-anion, Mg- and mixed-cation-SO_4, and Mg- and mixed-cation-Cl.

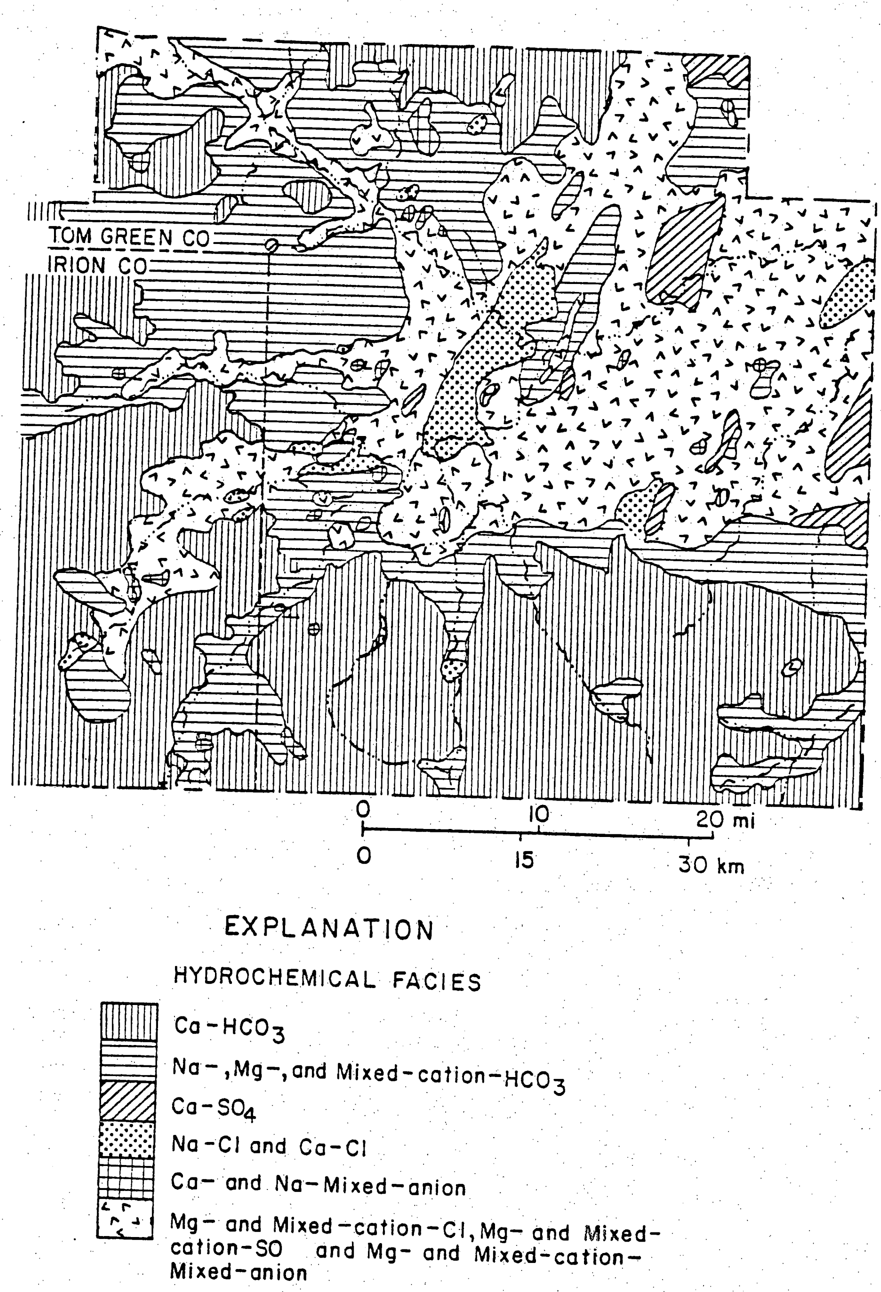

Figure 9. Map of hydrochemical facies in shallow aquifers of Tom Green and eastern Irion County. Isolated occurrences of Na-Cl, $Ca\text{-}SO_4$, and Na– and Ca–mixed-anion hydrochemical facies are anomalous within regions dominated by $Ca\text{-}HCO_3$ and Na– and Mixed-cation–HCO_3 facies in western Tom Green and eastern Irion Counties and suggest contamination by oil field brine. Well locations of samples shown in figures 5 to 7.

Table 3. Chemical and isotopic analyses of water-well and test-hole samples collected for this study. (Concentrations in mg/L except where indicated otherwise

Land Owner	Id	Depth (ft)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	TDS	pH	$\delta^{18}O$ (°/oo)	δD (°/oo)
Corbell	1	65	169	132	149	1	500	121	520	1506	6.9	-5.12	-37.0
Sollars	2	85	133	59	79	2	490	65	200	832	6.9	-4.75	-35.0
Hardy	3	95	230	112	691	6	385	183	1425	3179	6.9	-3.66	-29.7
Bailey	4	58	580	200	2670	59	340	590	5280	10000	7.5	n.a	n.a.
Red Arroyo	5a	7	820	920	3960	47	725	4100	6430	17335	7.3	-2.54	-23.7
Red Arroyo	5b	68	1890	760	19730	270	500	3695	33140	59259	7.1	-5.40	-35.3
King	6	50	254	319	1020	7	860	1430	1430	5332	6.7	-4.74	-34.2
Stovall	7a	32	130	43	320	10	330	232	335	1589	7.7	-4.00	-31.0
Stovall	7b	68	465	195	2790	53	340	515	5030	9615	7.5	-4.17	-31.0
Stovall	7c	75	610	240	4640	80	335	810	8070	15061	7.6	-4.14	-34.6
Williams	8	95	530	165	695	11	330	224	2100	4398	7.0	-4.06	-32.7
Ducote	9	46	1465	430	11540	265	555	645	20750	35446	6.7	-3.21	-28.4
Bunyard	10	24	750	270	6920	175	365	520	12190	21482	7.2	n.a.	n.a.
Chandler	11	38	990	350	1540	32	400	2080	3630	9390	7.2	-1.90	-19.2
Chandler	12	30	455	130	880	7	530	820	1650	4363	6.9	-0.42	-9.7
Latham	13	52	228	80	353	1	400	138	840	2124	6.8	1.77	0.2
Hoelscher	14	105	516	180	687	3	320	310	2040	4559	6.8	-1.97	-23.1
Baxter	15	100	472	150	659	4	350	357	1780	4178	6.7	-1.86	-22.8
Schwartz	16	100	476	151	662	3	340	353	1810	4006	6.7	-1.91	-23.0
Gully	17	90	414	121	314	4	240	106	1300	2869	6.8	-3.55	-32.2
Lawnhaven	18	120	413	144	346	5	270	487	1060	3058	7.2	-4.28	-35.3
Lawnhaven	19	100	286	118	340	4	210	298	920	2533	7.0	-4.02	-32.7
McClure	20	76	492	185	623	20	275	350	1880	4329	6.8	-3.78	-32.1
Wash. Cty	21	160	1290	540	11240	155	435	3130	19380	36082	7.5	n.a.	n.a.
Wash. Cty	22	6212	1720	950	16960	320	250	4310	29610	54312	7.6	n.a.	n.a.
Jost	23	75	730	310	2710	50	430	2500	4450	11629	7.3	n.a.	n.a.
Keyes	24	42	1730	1050	4910	57	265	905	13070	22740	6.9	n.a.	n.a.

....

n.a. not analyzed

Table 3. (cont.)

Id	Ba	Fe	Li	Sr	Br	I	B	NO_3	Acet.	Prop.
1	Ø.32	<Ø.Ø2	<Ø.Ø3	2.81	2.6	1.Ø	Ø.Ø7	13	n.a.	n.a.
2	Ø.12	<Ø.Ø2	<Ø.Ø3	3.63	1.9	<1.Ø	Ø.Ø6	24	n.a.	n.a.
3	Ø.Ø8	<Ø.Ø2	<Ø.Ø3	4.52	4.7	<1.Ø	Ø.27	59	n.a.	n.a.
4	Ø.3	1.Ø	2.2	9.8	8.5	Ø.3	2.3	24	n.a.	n.a
5a	Ø.4	Ø.4	2.1	13.Ø	14.Ø	2.Ø	4.1	<2	n.a.	n.a.
5b	<Ø.1	3.1	8.1	46.Ø	61.Ø	2.4	1Ø.Ø	<2	<1.	<1.
6	Ø.Ø7	<Ø.Ø2	<Ø.Ø3	9.Ø1	5.6	2.Ø	2.Ø9	18	n.a.	n.a.
7a	Ø.2	Ø.4	Ø.6	1.3	1.8	1.Ø	<2.Ø	242	n.a.	n.a.
7b	Ø.4	Ø.1	1.2	8.1	9.6	1.Ø	<2.Ø	1Ø2	n.a.	n.a.
7c	Ø.4	Ø.9	1.4	11.Ø	16.Ø	2.1	2.Ø	7Ø	<1.	<1.
8	Ø.2	<Ø.1	Ø.5	7.2	3.Ø	<1.Ø	<2.Ø	65	n.a.	n.a.
9	Ø.7	6.4	4.6	47.Ø	35.Ø	4.Ø	6.1	57	<1.	<1.
1Ø	Ø.5	1.8	5.Ø	19.Ø	15.Ø	Ø.5	5.2	74	<1.	<1.
11	Ø.3	Ø.4	1.1	7.3	8.4	3.Ø	<2.Ø	11	n.a.	n.a.
12	<Ø.1	Ø.4	Ø.8	4.2	4.9	1.6	<2.Ø	<2	n.a.	n.a.
13	Ø.13	<Ø.Ø2	<Ø.Ø3	3.14	2.3	4.Ø	Ø.45	8	n.a.	n.a.
14	Ø.11	<Ø.Ø2	<Ø.Ø3	6.43	7.8	<1.Ø	Ø.44	75	n.a.	n.a.
15	Ø.Ø6	Ø.19	<Ø.Ø3	5.36	6.6	1.Ø	Ø.41	62	<1.	<1.
16	Ø.Ø9	<Ø.Ø2	<Ø.Ø3	5.94	4.6	3.Ø	Ø.37	66	n.a.	n.a.
17	Ø.28	<Ø.Ø2	<Ø.Ø3	5.17	5.6	<1.Ø	Ø.16	69	n.a.	n.a.
18	Ø.Ø8	<Ø.Ø2	<Ø.Ø3	14.4	4.8	<1.Ø	Ø.27	71	n.a.	n.a.
19	Ø.Ø8	<Ø.Ø2	<Ø.Ø3	5.27	3.9	<1.Ø	Ø.19	138	n.a.	n.a.
2Ø	Ø.1Ø	<Ø.Ø2	<Ø.Ø3	7.81	6.2	<1.Ø	Ø.23	85	<1.	<1.
21	Ø.3	1.3	5.Ø	27.Ø	4Ø.Ø	1.6	5.9	<2	n.a.	n.a.
22	Ø.6	3.7	3.3	343.Ø	33.Ø	2.1	11.Ø	<2	3.	<1.
23	Ø.4	1.5	2.5	13.Ø	6.6	<Ø.2	4.4	<2	<1.	<1.
24	Ø.4	1.3	3.4	36.Ø	22.Ø	Ø.7	<4.Ø	32	<1.	<1.

Acet. - acetate
Prop. - propionate

investigations (for example, Willis, 1954, and Lee, 1986) predominantly have low TDS. Hydrochemical facies of these samples include Ca-HCO_3, mixed-cation-Cl, and Na-Cl types.

Occurrence of salt water at shallow depth is not a recent phenomenon, having been noted in Tom Green County during the early 1900's (Udden and Phillips, 1911). The San Angelo Formation has long been known to contain salty water at shallow depth. To obtain undisturbed ground-water samples from the San Angelo Formation, two test holes (no. 4 and no. 5, table 3 and fig. 10) were drilled at or near the San Angelo Formation outcrop (fig. 1). Water samples obtained from these test holes had high chloride concentrations. Chloride concentrations in test hole no. 5, drilled next to a tributary of Red Arroyo in San Angelo, increased from 6,430 mg/L at 7-ft (2-m) depth to 33,140 mg/L at a 68-ft (20-m) depth below land surface. Twelve hours after this well was drilled, hydrogen-sulfide brine started flowing at land surface from 68 ft (20 m) below land surface. In test hole no. 4, also drilled within the city of San Angelo, water with a chloride content of 5,280 mg/L (no. 4, table 3) was encountered at 58 ft (17 m) below land surface.

Chloride is the dominant anion in all samples but one (no. 1, table 3) that were collected from water wells during this study (fig. 11). The two waters with the lowest salinity (no. 1 and no. 2) also have among the lowest proportions of dissolved sodium and chloride (fig. 11). Most samples with low TDS reported for Tom Green County are Ca-HCO_3 or mixed-anion-HCO_3 types, not Na-Cl types (compare figs. 5-7 with fig. 9). Sample no. 6 (table 3), having a relatively high sulfate concentration and a Mg/Ca ratio greater than one, has an unusual chemical composition compared with that of other samples. This sample was obtained from a water well that is located west of the Middle Concho River just north of

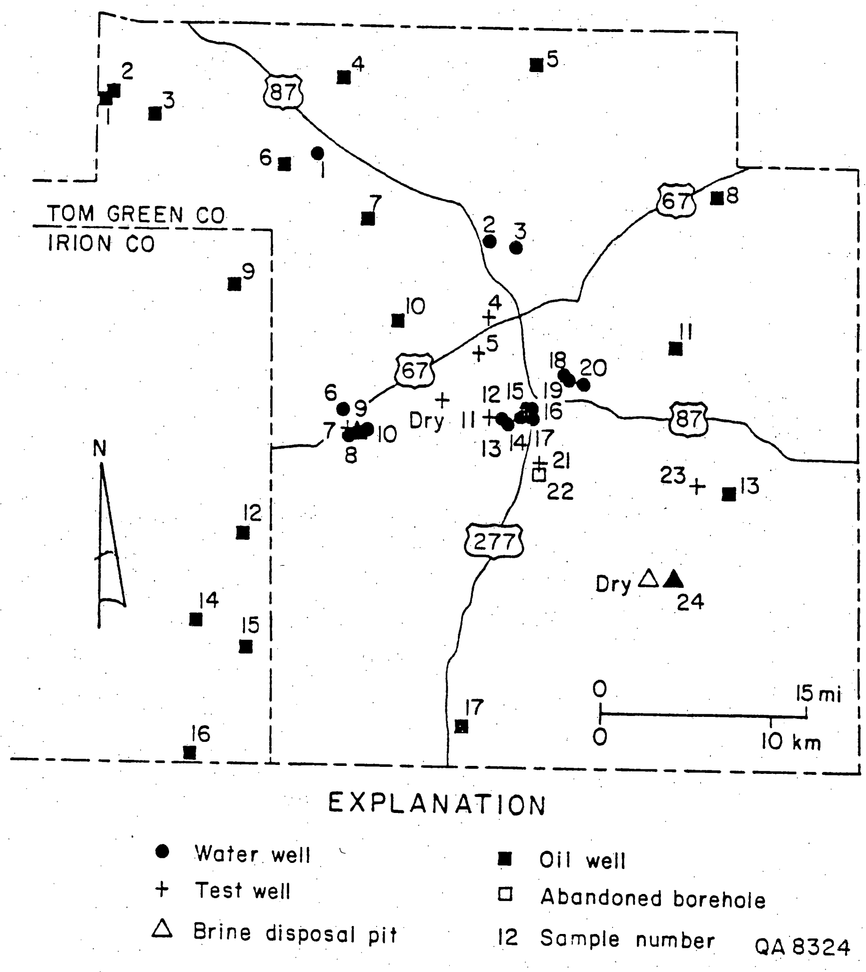

Figure 10. Location of test sites at which water samples were obtained.

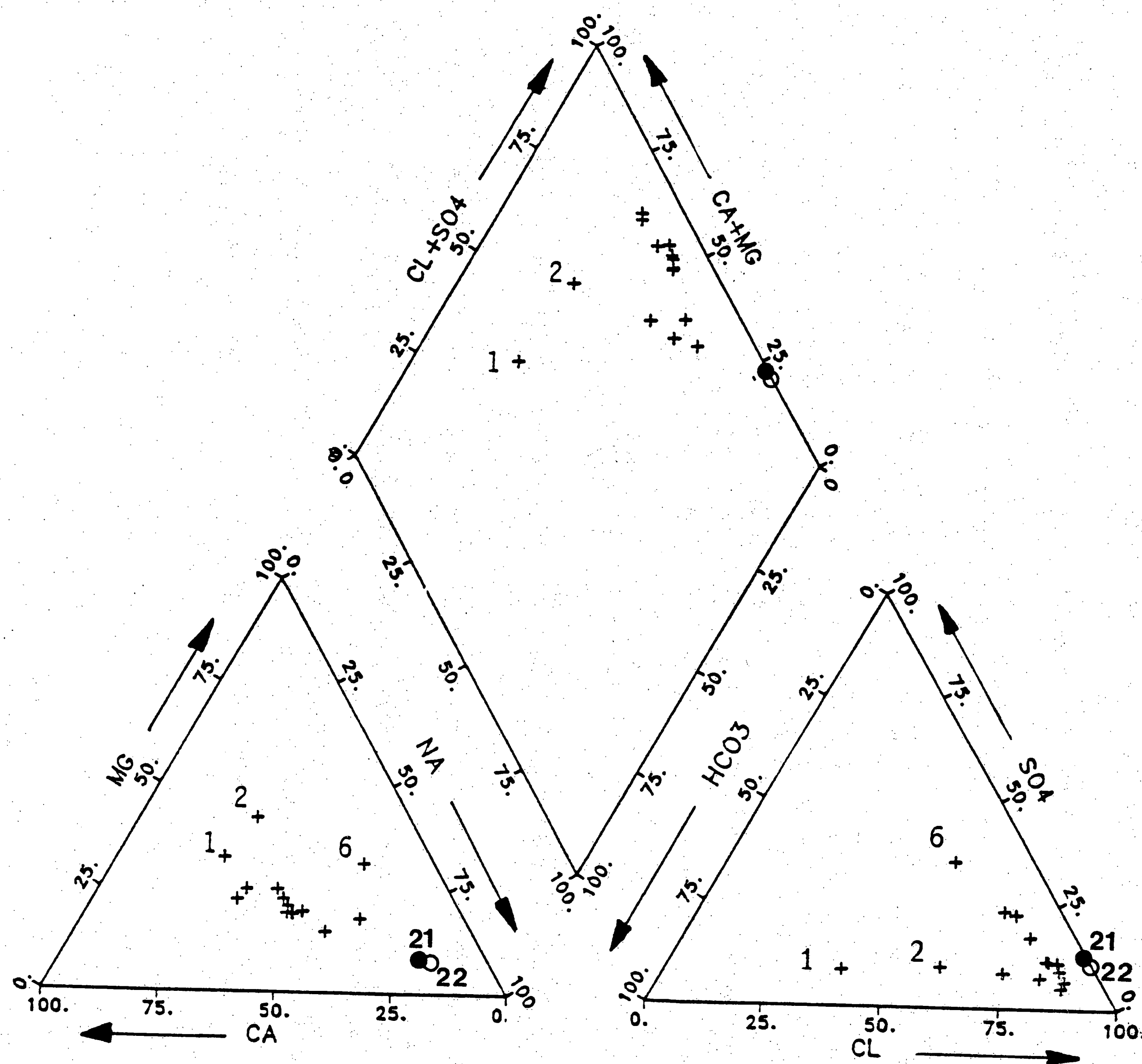

Figure 11. Piper diagram of hydrochemical facies of chloride-rich and other ground-water samples collected during this study.

Highway 67 (between San Angelo and Tankersley, fig. 10). Taken from a land surface elevation of approximately 30 ft (9 m) above the nearby Middle Concho River and a well depth of 50 ft (15 m), this water sample probably constitutes a mixture of local ground water and river water. The other water samples range from a mixed cation-chloride hydrochemical facies to a Na-Cl facies (fig. 11).

Calcium, magnesium, and sodium concentrations in water-well samples increase with increasing chloride concentrations (fig. 12). The covariance between the cationic and chloride ionic concentrations is small. The Br/Cl ratios vary widely and decrease with increasing chloride concentration (fig. 12). In plots of chemical constituents of water-well and test-hole samples, ratios of Ca/Cl, Na/Cl, and K/Cl seem to be fairly constant over the range of chloride concentrations (figs. 13 and 14). Ratios of SO_4/Cl and Mg/Cl of test-hole samples vary considerably over the range of chloride concentrations (figs. 13 and 14). Test-hole and water-well samples show distinctly different Br/Cl ratios (fig. 14).

Chemical Characterization of Brines

Chemical and isotopic compositions of 17 subsurface brines collected from oil wells in Tom Green and eastern Irion Counties are listed in table 4. The brines do not form distinct groups or associations but appear as a continuous array (fig. 15). One end member of the array (SA), represented by San Andres, San Angelo, and Clear Fork brines, plots close to the meteoric water line and is isotopically similar to shallow ground waters measured by Richter and Kreitler (1985). Brine samples from the Canyon and Strawn fields define another end member (C/S) in this and subsequent plots. This end member plots to the right

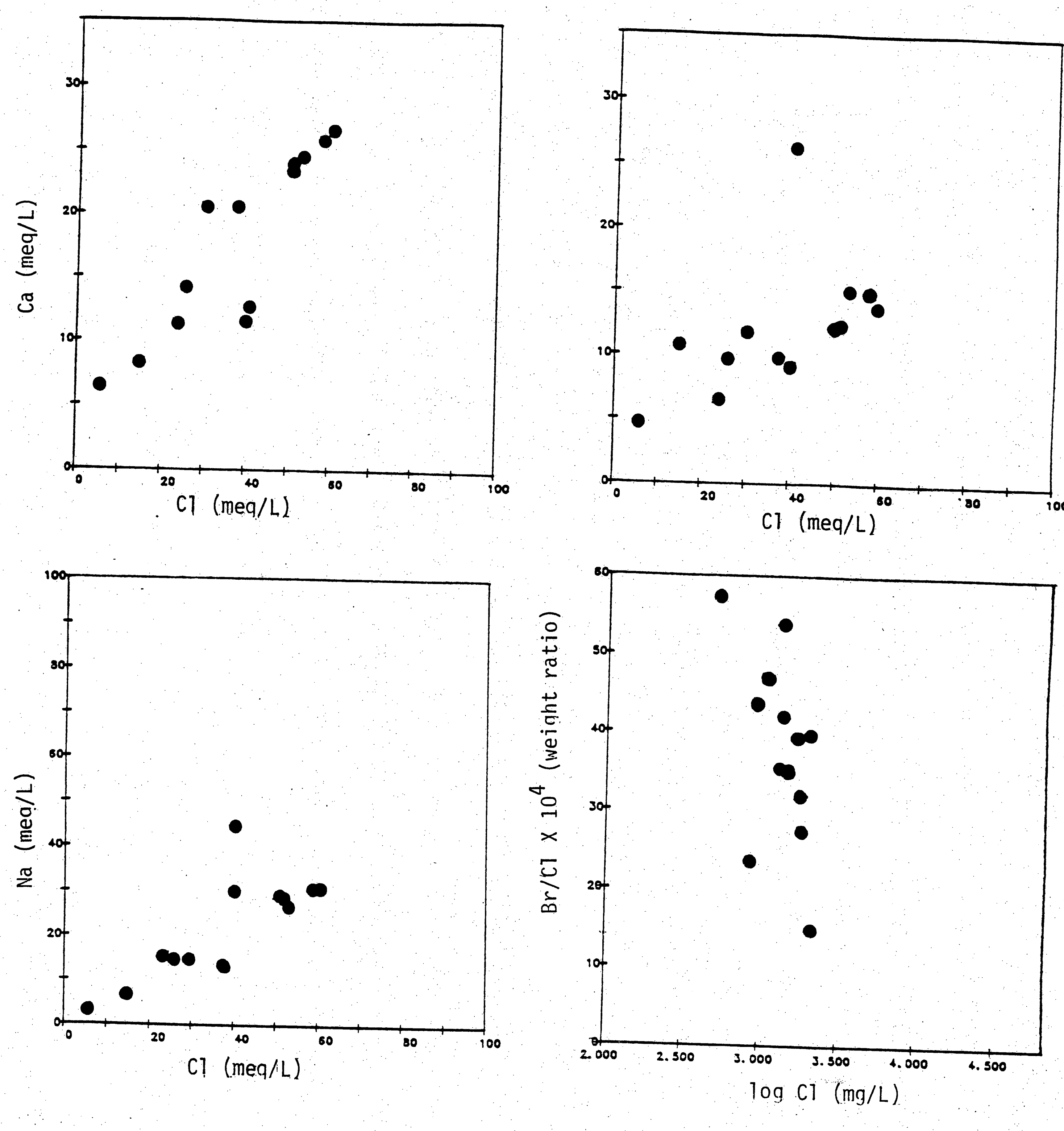

Figure 12. Plots of Ca, Mg, and Na concentrations and of Br/Cl ratios versus Cl for chloride-rich and other ground-water samples collected during this study.

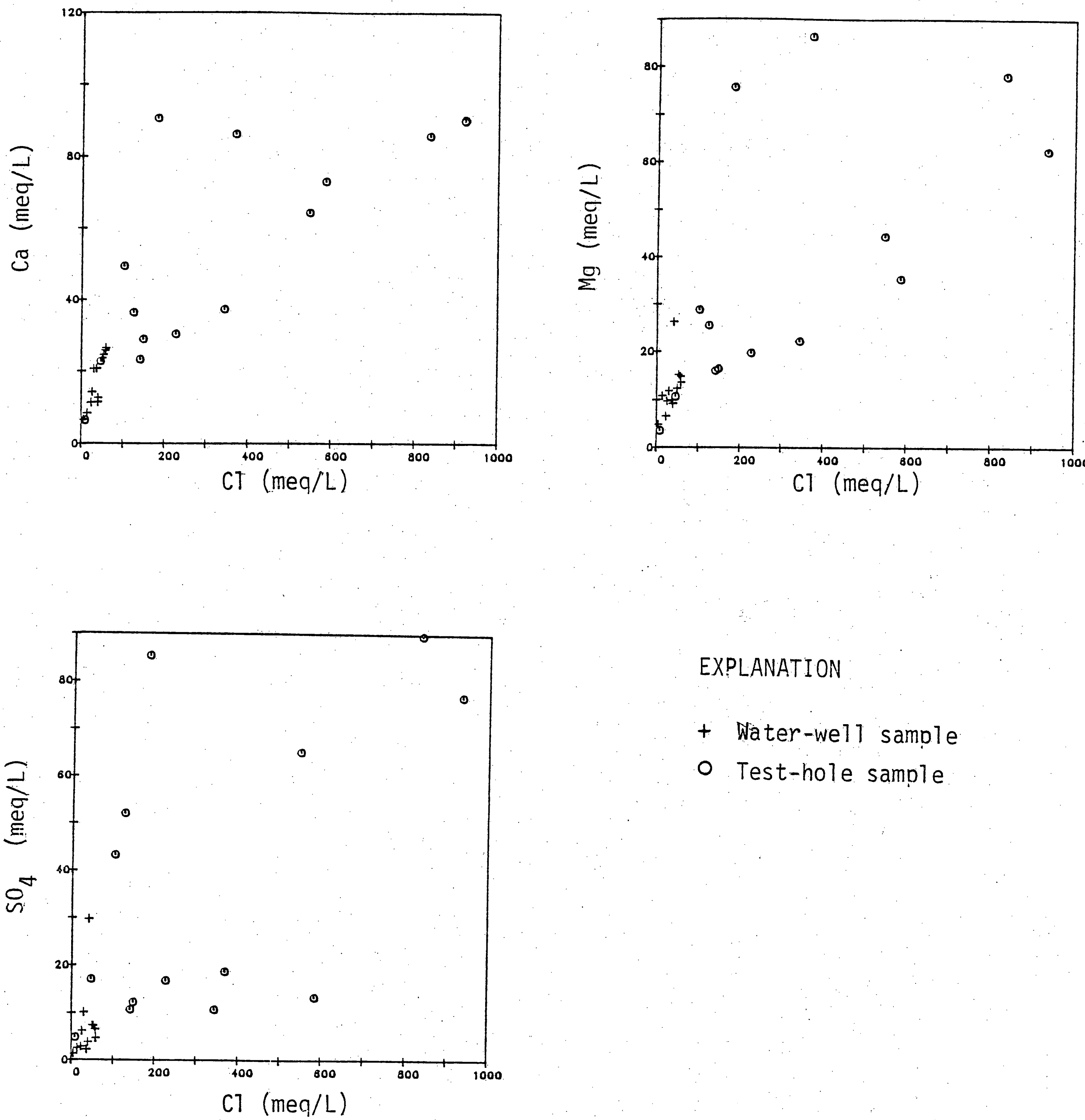

Figure 13. Plots of Ca, Mg, SO_4, and Cl concentrations in water-well and test-hole samples. Samples from water wells, shown here and in figure 12, generally have lower Ca, Mg, SO_4, and Cl concentrations than samples from test wells.

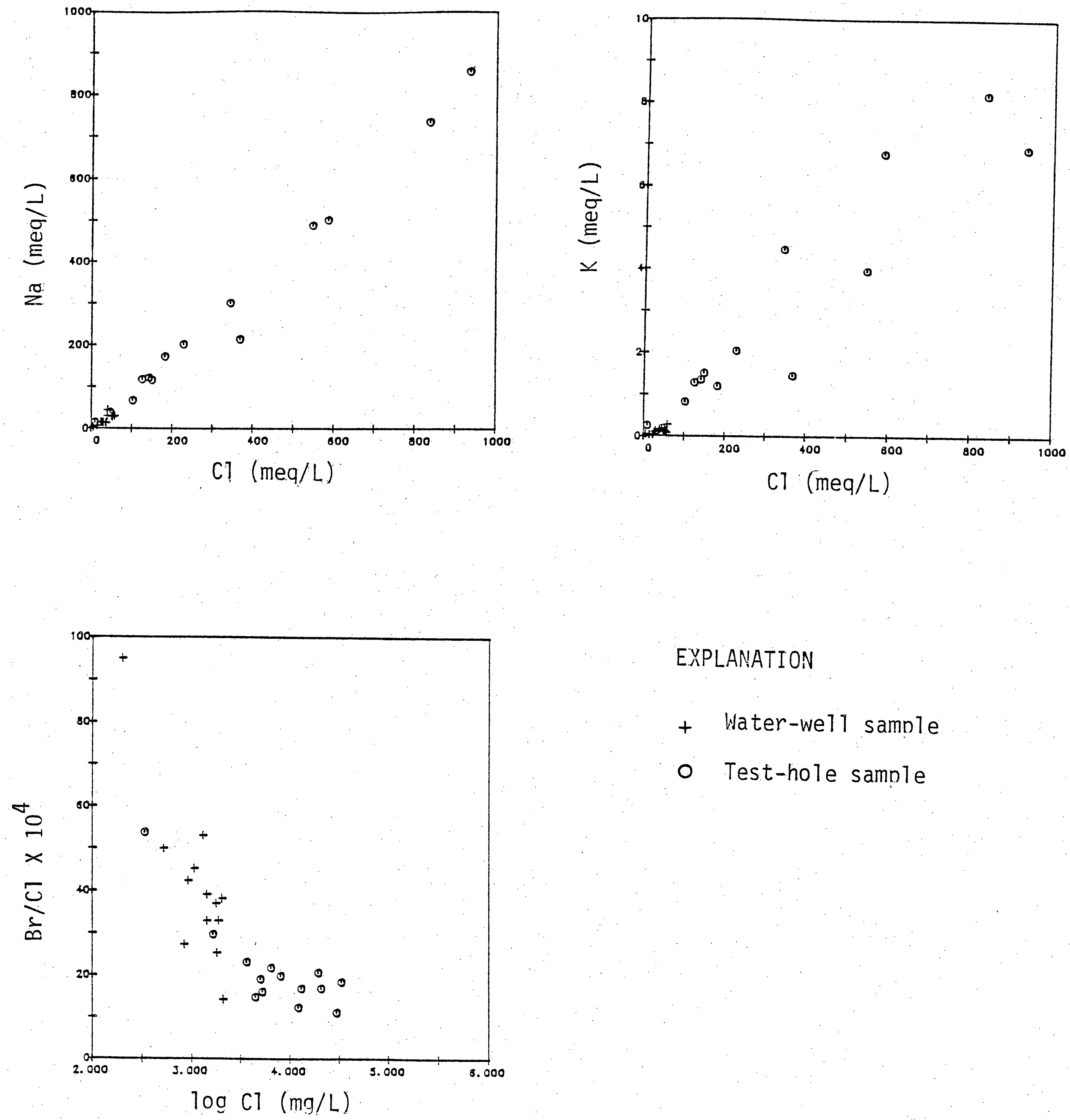

Figure 14. Plots of Na, K, and Cl concentrations and Br/Cl ratios for water-well and test-hole samples. Samples from water wells, shown here and in figure 12, generally have lower Na, K, and Cl concentrations and higher Br/Cl ratios than samples from test wells.

Table 4. Chemical composition of subsurface brine collected from oil wells in Tom Green and eastern Irion Counties (concentrations in mg/L).

No.	Field	Formation	Depth (ft)	Temp. °C	pH	Ca	Mg	Na	K	HCO_3	SO_4	Cl	δD (°/oo)	$\delta^{18}O$ (°/oo)	$\delta^{34}S-SO_4$ (°/oo)
1	Water Valley	San Andres	1000	25.	7.65	1980	867	32620	399	297.13	1860	52620	-34,-35	-5.2	35.08,35.68
2	Water Valley	Clear Fork	1500	25.5	6.65	2240	822	29750	445	797.44	3490	47680	-37	-5.2	..
3	Hall	San Andres	1800	31.	6.85	2410	1330	28930	488	611.96	3230	48510	-33,-35	-2.0	27.84,28.30
4	Carlsbad	Strawn	5860	23.5	5.8	13970	2960	62400	545	72.60	19	119850	-8	-0.1	21.22
5	Eliza Baker, N.	Canyon	6500	22.	6.5	9970	1970	40560	1050	145.82	760	81470	-32	-4.0	19.07
6	T.D. (6575)	Strawn	6900	30.	6.6	10150	1680	53660	397	212.32	10	102840	-12	+0.3	..
7	KWB	Strawn	7500	26.	6.5	13040	1640	55590	320	131.79	24	113140	-11	+0.6	13.00
8	SSR	Canyon	4300	29.5	6.9	9560	1530	40840	450	81.15	660	78960	-16	-3.0	22.45
9	Arden	Canyon	6500	33.	6.32	11350	1610	54790	534	195.85	10	105300	-8,-9	-0.2	22.86
10	Pulliam	Canyon	5200	42.	6.8	9530	1610	43940	445	115.92	540	86150	-19	-0.8	20.55
11	Veribest	Strawn	4700	25.5	6.3	13110	1830	43820	250	20.13	53	90740	-9	-1.1	19.45,19.3[illegible]
12	Brooks	San Angelo	1300	26.	7.4	831	599	15840	206	198.29	20	26360	-35	-4.8	40.26
13	Halfman	Strawn	4700	32.	6.2	8230	1510	38180	593	204.39	950	74250	-22,-27	-3.1	18.97
14	Mim, NW	San Angelo	1100	27.5	6.35	1290	701	27100	216	294.08	10	42790	-27	-4.0	..
15	Dove Creek	Canyon	6700	33.5	6.3	12740	1830	61420	431	71.99	11	123600	-12,-15	+0.4,+0.7	10.31
16	Tankersley	Wolfcamp	5500	40.	6.55	50960	2780	47460	2560	93.96	350	176320	+8	+6.2,+6.2	14.15
17	H-J	Strawn	5500	34.5	7.15	2980	682	29180	741	362.42	1240	49520	-44	-5.5	22.28

.. - indicates sample not analyzed

Table 4 (cont.)

No.	Field	Formation	$\delta^{13}C$ (°/oo)	Ba	Fe	Li	Mn	Sr	Br	I	TOC	Acet.	Prop.
1	Water Valley	San Andres	-23.91	0.25	223	3.6	4.22	59.1	67	2	*21	<1	<1
2	Water Valley	Clear Fork	-19.42	0.15	0.2	3	2.29	52.4	73	1	80	<1	<1
3	Hall	San Andres	-11.79	0.62	102	3.8	3.46	52	61	3	82	85	2
4	Carlsbad	Strawn	-8.76	30.40	291	13.2	3.96	1020	460	39	80	128	14
5	Eliza Baker, N.	Canyon	-3.05	0.89	70	16.9	0.51	357	200	8	52	107	11
6	T.D. (6575)	Strawn	-2.37	178	185	6.6	3.29	587	410	34	88	187	15
7	KWB	Strawn	-3.82	450	153	15.8	5.78	1320	450	28	128	228	13
8	SSR	Canyon	-4.26	1.85	108	12.9	4.73	375	280	12	82	130	12
9	Arden	Canyon	-4.40	56.70	344	11.5	4.35	819	430	27	130	136	14
10	Pulliam	Canyon	-3.16;-2.89	1.42	19.6	12.9	0.51	378	350	12	52	89	7
11	Veribest	Strawn	-6.45	5.20	85	11.4	4.93	598	360	14	70	137	22
12	Brooks	San Angelo	-19.62	0.37	0.1	3.4	7.47	39.4	360	1	*8	2	<1
13	Halfman	Strawn	+0.55	0.60	86	16.1	0.59	269	230	9	38	79	1
14	Mim, NW	San Angelo	-25.42	0.33	0.2	5.7	0.25	73.8	60	3	*2	<1	<1
15	Dove Creek	Canyon	-7.65	131	142	8.4	5.74	769	480	51	102	140	11
16	Tankersley	Wolfcamp	-0.90	17.40	1300	4.9	14.90	547	320	75	510	725	6
17	H-J	Strawn	+1.5;+1.58	0.39	1.2	10.3	0.26	120	50	1	38	27	4

* - indicates below detection limit
TOC - total organic carbon
Acet. - acetate
Prop. - propionate

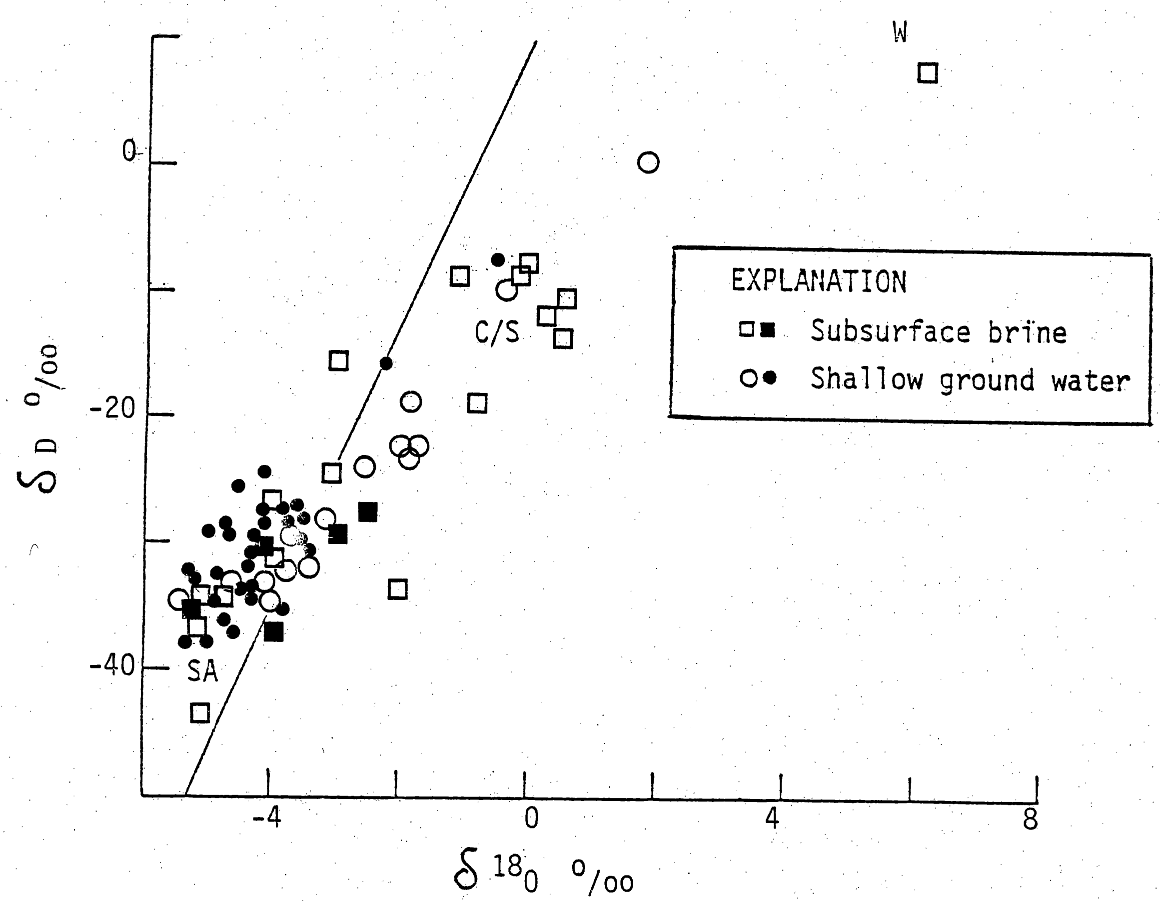

Figure 15. Variation in δD and $\delta^{18}O$ in brines and shallow ground water from Tom Green, eastern Irion, Concho, and Runnels Counties. Brine end members marked by: SA - San Andres/San Angelo/Clear Fork, C/S - Canyon/Strawn, and W - Wolfcamp. Line shows meteoric water line defined by $\delta D = 10 + 8\ \delta^{18}O$ (Craig, 1961).

of the meteoric water line; the Wolfcamp sample (W) plots particularly far from the meteoric water line. Differences between end members defined by samples from the Permian units and Pennsylvanian units do not simply reflect differences between shallow and deep waters, however, because two deep Strawn samples (Eliza Baker North and H-J, samples 5 and 17 [table 4]) are similar to the San Andres/San Angelo/Clear Fork end member. Most shallow ground-water samples plot closer to San Andres/San Angelo/Clear Fork samples than to deep Canyon and Strawn samples.

The Br/Cl ratio in subsurface brines increases with increasing chloride concentration and shows end members similar to those of previous plots (fig. 16). The Br/Cl ratio of the Canyon/Strawn end member is similar to that of most deep-basin brines (Whittemore, 1984; Richter and Kreitler, 1986). The San Andres/San Angelo/Clear Fork subsurface brine end member has a Br/Cl ratio similar to that derived from halite dissolution. In contrast, the Br/Cl ratios of shallow ground waters from Tom Green, Runnels, and Concho Counties decrease with increasing chloride concentration. Ground-water samples with the highest chlorinity and lowest Br/Cl ratio plot near the San Andres/San Angelo/Clear Fork subsurface brine end member (fig. 16).

Alkalinity, which is the ability of a water to neutralize acid, may distinguish brine sources from shallow and deep oil fields. Alkalinity of subsurface brine at depths of 1,000 to 1,800 ft (300 to 550 m) in San Andres and San Angelo oil fields is due to dissolved bicarbonate ions; alkalinity of brine in deeper Pennsylvanian and in Wolfcamp fields is primarily due to dissolved short-chain aliphatic acid (carboxylic acid) anions (table 4). Acetate and propionate ions account for 61% to 98% of total organic carbon (TOC) in samples with organic

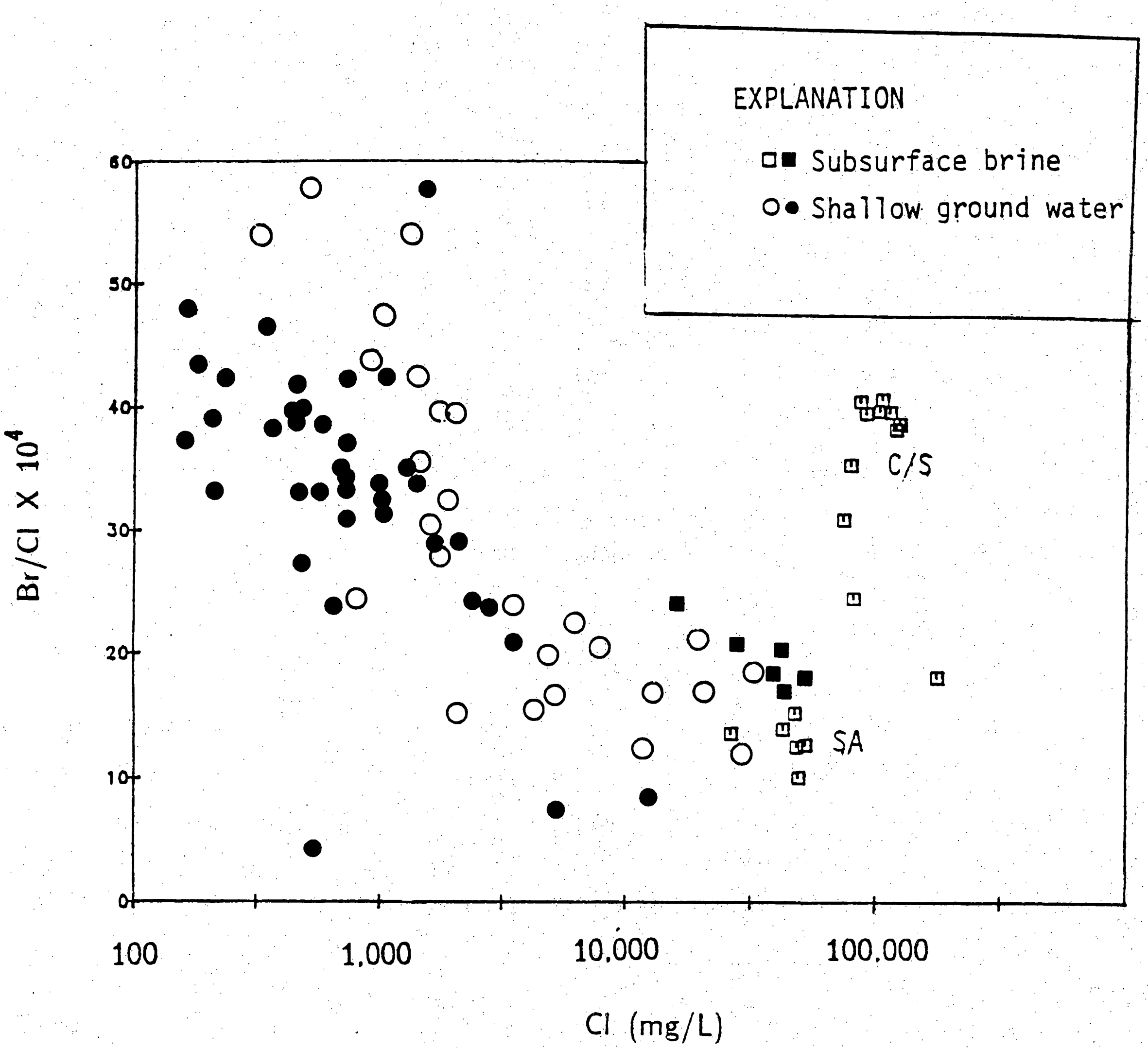

Figure 16. Br/Cl ratios in subsurface brines and shallow ground waters in Tom Green, eastern Irion, Runnels, and Concho Counties. Brine end members SA, C/S, and W as identified in figure 15.

ions; analytic error and possible presence of organic ions other than the aliphatic acid anions account for the discrepancy.

Acetate concentration varies directly with $\delta^{18}O$ (fig. 17). The San Andres/San Angelo/Clear Fork end member has low acetate concentration, high bicarbonate alkalinities, and the most negative $\delta^{18}O$ and $\delta^{13}C$ (fig. 18) values. The Canyon/Strawn end member has greater acetate concentrations and more positive $\delta^{18}O$; the sample from a Wolfcamp field has the highest acetate concentration (fig. 17) and very enriched $\delta^{18}O$ and $\delta^{13}C$ compositions (fig. 18).

A continuous array is not well defined in a plot of $\delta^{34}S$ versus dissolved SO_4 concentrations, although previously defined end members are recognizable (fig. 19). Sulfate concentration is probably controlled by formation temperature and activity of sulfate-reducing bacteria and tends to decrease with depth. High SO_4 concentrations in shallow Permian formations might reflect (1) dissolution of bedded anhydrite, (2) low activity of sulfate-reducing bacteria, or (3) oxidation of sulfides as subsurface brines move along regional flow paths into shallower depths across the Eastern Shelf. Some of the subsurface brines have $\delta^{34}S$ values similar to values typical of Paleozoic sulfate-bearing rocks (Holser, 1979), possibly reflecting dissolution of anhydrite. Other brines throughout the stratigraphic section have significantly enriched $\delta^{34}S$ compositions; these more positive $\delta^{34}S$ values most likely result from sulfate reduction by bacteria.

In Tom Green County, three brine systems are capable of contaminating shallow ground water. First, the most shallow aquifer units with salinity problems in the area are in the San Angelo and San Andres Formations and the Clear Fork

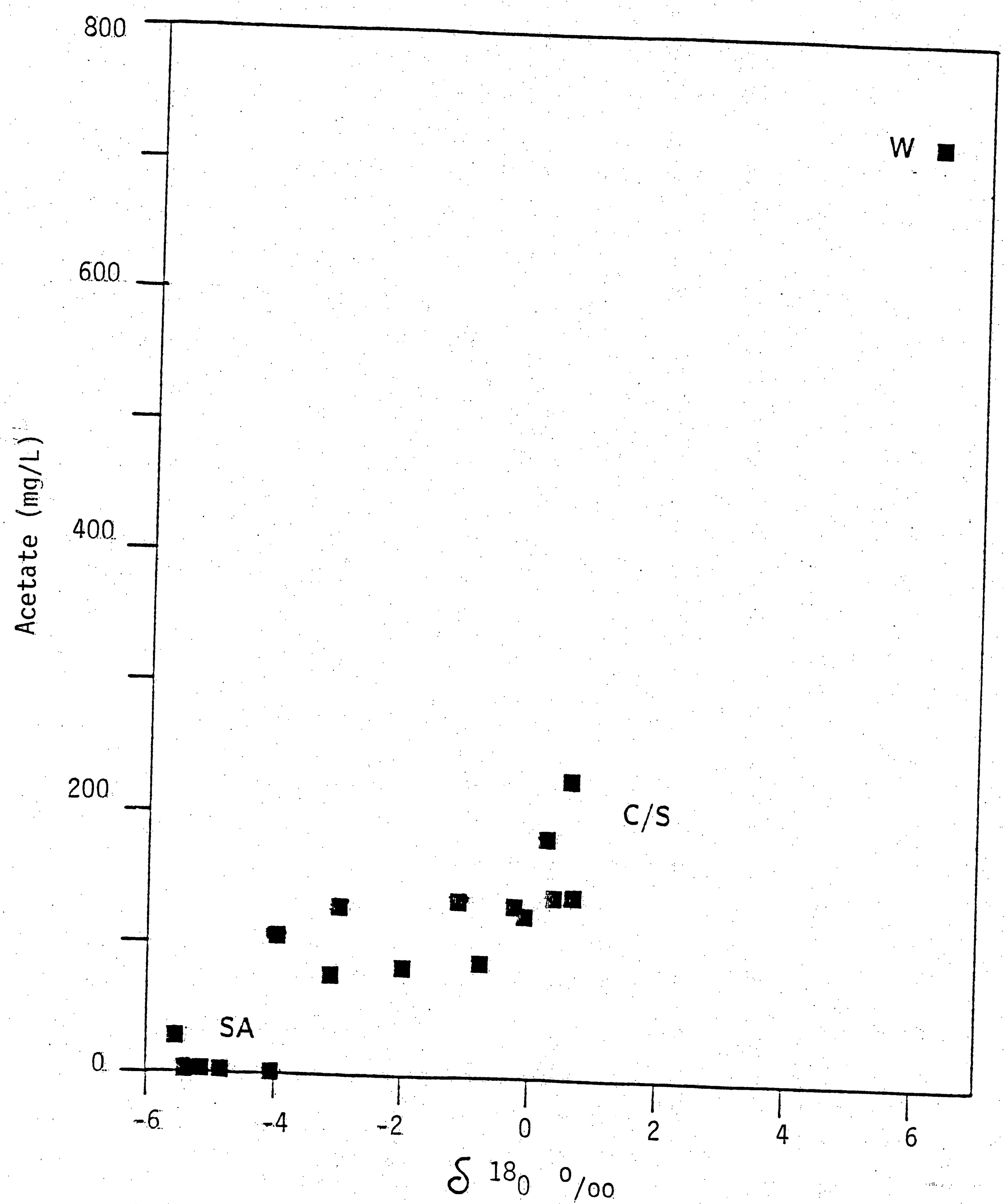

Figure 17. Plot of acetate versus $\delta^{18}O$ for subsurface brines from Tom Green and eastern Irion Counties. Brine end members SA, C/S, and W identified in figure 15.

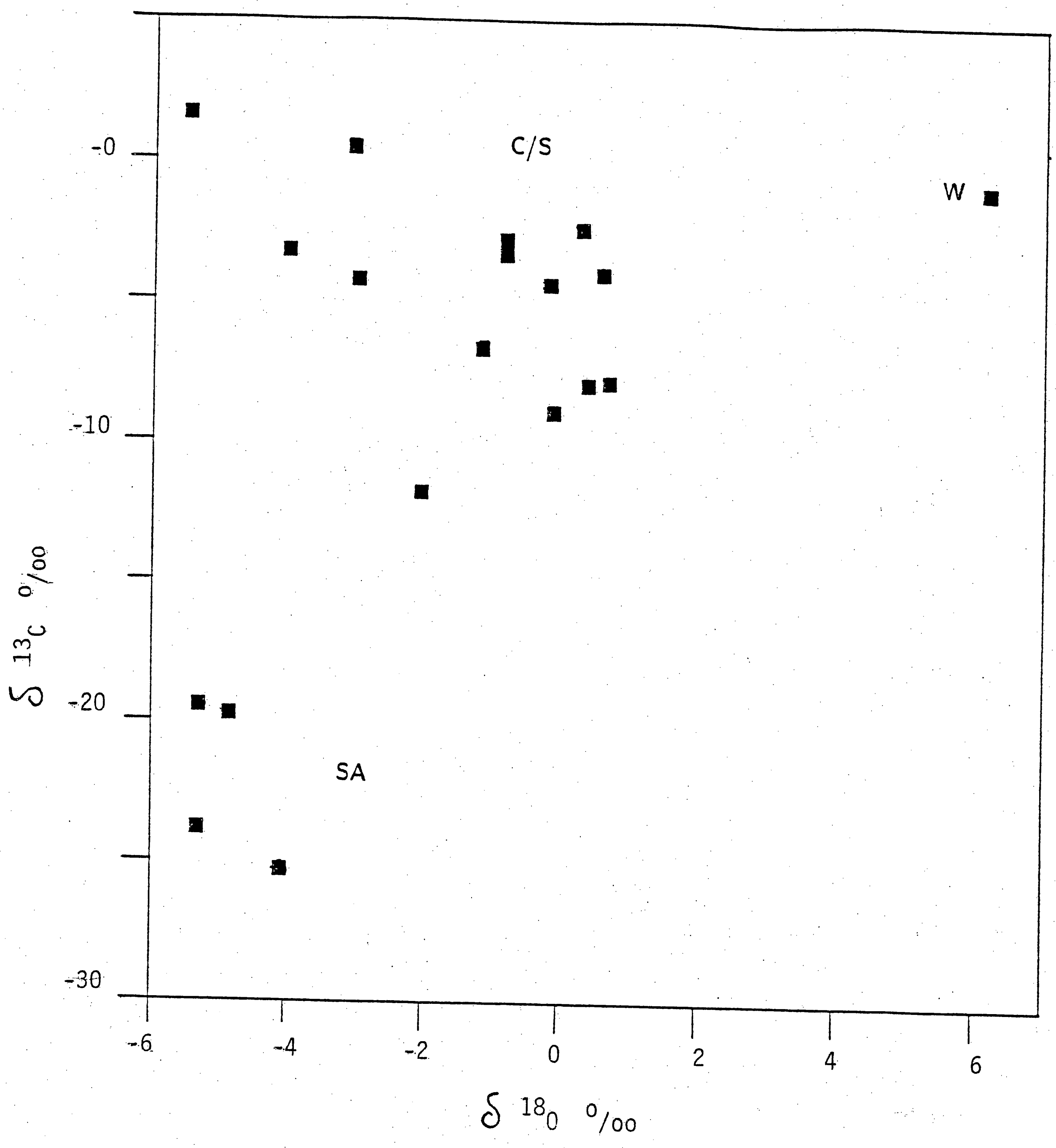

Figure 18. Plot of $\delta^{13}C$ versus $\delta^{18}O$ in subsurface brines from Tom Green and eastern Irion Counties. Brine end members SA, C/S, and W identified in figure 15.

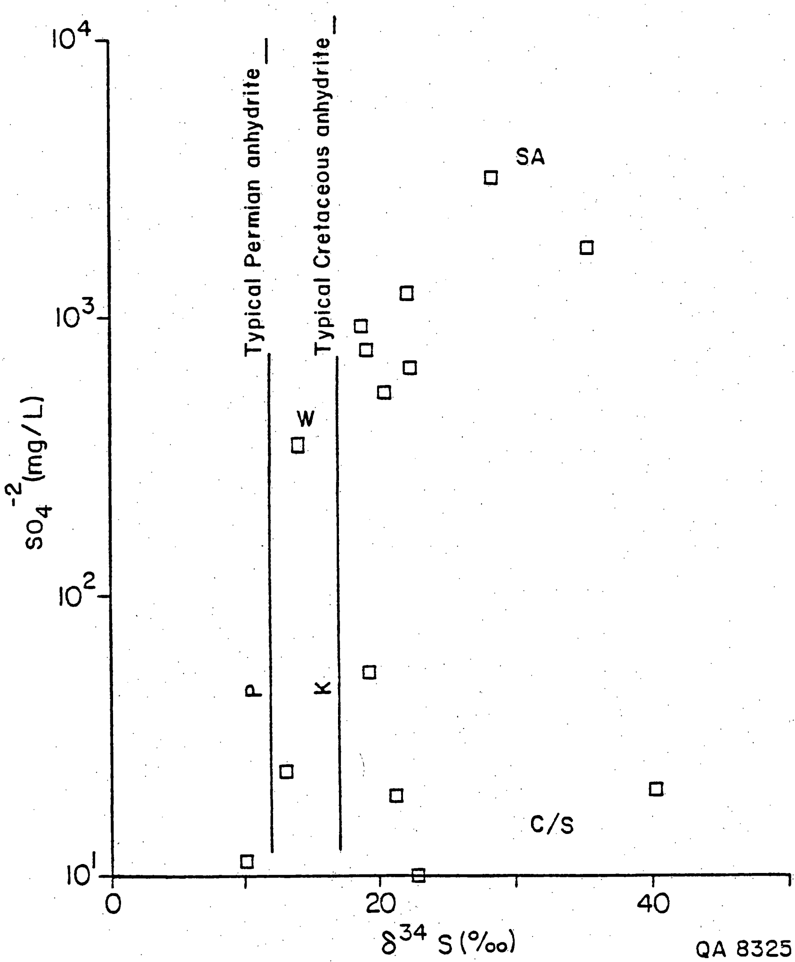

Figure 19. Relation between $\delta^{34}S$ and sulfate concentration in subsurface brines from Tom Green and eastern Irion Counties.

Group. In western Tom Green County, 30 ft (9 m) of shale separates the San Andres from the San Angelo Formation; this shale is absent in the center and northern part of Tom Green County (T. L. Koederitz, personal communication, 1987). Oil is produced from these strata at depths of 900 to 1,200 ft (270 to 360 m) below land surface in the western part of Tom Green County. Eight samples from San Angelo, San Andres, and Clear Fork fields were selected to characterize the composition of these shallow brines (table 5). Second, the Coleman Junction Formation underlies the county at depths of approximately 3,000 (900 m) ft in the west and 1,000 ft (300 m) in the east. Brine flows to land surface from this unit in most cases where a pathway exists. Because of the lack of chemical data from the Coleman Junction Formation in Tom Green County, 14 reported brine analyses of water samples (table 5) outside the county were used to investigate its chemical characteristics. Third, most oil production in Tom Green County is from Pennsylvanian strata. Therefore, Pennsylvanian brines can contact shallow ground water where oil production or brine-disposal methods have been faulty.

Brines in Pennsylvanian units have higher Cl, Ca, Mg, and Na concentrations but lower sulfate concentrations than the analyzed brines from Permian units (fig. 20). Brines from the Coleman Junction Formation show the least scatter, although data were combined from six counties. This suggest that brine composition in the Coleman Junction Formation is uniform throughout an area extending 150 mi (240 km) north from Tom Green County to Knox County. Brines from San Angelo/San Andres/Clear Fork units have a similar average chemical composition but greater variability (fig. 20). Therefore, Coleman Junction brines cannot be distinguished from San Angelo/San Andres/Clear Fork brines at shallow depths using these chemical indices. Brines that were collected at land surface by the district office of the Railroad Commission of Texas (table 5) from

Table 5. Chemical analyses of brines from San Angelo, San Andres, Clear Fork, Coleman Junction, and Pennsylvanian units. Also listed are chemical analyses from samples collected at various surface leaks by the Railroad Commission of Texas. (Concentrations in mg/L.)

County	Ca	Mg	Na	Alkalinity mg/L	SO_4	Cl	Source
			San Angelo, San Andres, Clear Fork				
Tom Green	1890	760	19730	500	3695	33140	
Tom Green	849	769	16050	355	864	27420	a
Tom Green	931	696	15600	548	9	27200	b
Tom Green	2460	1050	16000	405	3180	19500	c
Tom Green	2880	880	37500	427	4160	62200	c
Tom Green	1980	867	32620	300	1860	52620	
Tom Green	2240	822	29750	800	3490	47680	
Irion	831	599	15840	200	20	26360	
Tom Green	2410	1330	28930	700	3230	48510	
Irion	1290	701	27100	295	10	42790	
			Coleman Junction				
Tom Green	1720	950	16960	250	4310	29610	
Runnels	1940	1059	22500	1	2310	38000	b
Runnels	2500	1122	22900	164	4170	38300	b
Coke	2298	1070	28727	277	3575	48200	b
Coke	2033	942	22013	561	4676	36524	d
Coke	3060	1070	27800	340	3620	48400	d
Fisher	2490	855	20600	470	2850	36100	d
Knox	3150	1051	26642	201	3266	47162	d
Runnels	2530	994	25200	188	3800	43200	d
Jones	2664	459	22460	122	4400	37400	e
Jones	1520	864	15940	149	2000	28500	e
Jones	2120	750	23500	180	3700	39500	e
Jones	2376	730	19150	251	4240	32600	e
Jones	1570	620	21200	212	4300	34000	e
Unknown	2400	975	27080	334	3670	46000	f
			Pennsylvanian				
Tom Green	9530	1610	43940	215	540	86150	
Tom Green	13040	1640	55590	380	24	113140	
Tom Green	10150	1680	53660	420	10	102840	
Irion	12740	1830	61420	225	11	123600	
Tom Green	9560	1530	40840	225	660	78960	
Tom Green	13110	1830	43820	180	53	90740	
Tom Green	9970	1970	40560	265	760	81470	
Tom Green	13970	2960	62400	215	19	119850	
Irion	11350	1610	54790	350	10	105300	
Tom Green	2980	682	29180	395	1240	49520	
Tom Green	8230	1510	38180	290	950	74250	

Table 5 (cont.)

	Ca	Mg	Na	Alkalinity mg/L	SO_4	Cl	Source
			Various Brines from Surface Leaks				
Runnles	4530	5	31600	985	3750	51600	b
Runnels	2400	881	26100	412	3930	41200	b
Runnels	1605	1110	7440	141	3390	15500	g
Runnels	2310	1120	25700	136	4080	41900	g
Concho	4350	1405	34250	121	3935	46370	g
Concho	2525	2440	7270	100	2950	27500	g
Irion	2720	171	32200	580	150	54600	g
Irion	3000	1	30700	494	452	56840	g
Irion	900	720	17350	362	69	31990	g
Runnels	2025	945	20650	63	3860	38000	g
Runnels	2625	1815	20825	204	3376	43520	g
Runnels	1084	644	7820	0	4260	12000	g
Runnels	2500	1200	22760	11	3800	42990	g
Runnels	2500	1525	25850	181	3632	37920	g
Runnels	1533	1080	6850	132	3580	14000	g
Runnels	2060	800	19320	55	2760	36130	g
Runnels	2800	1220	29800	155	4200	49100	g
Runnels	1540	1100	6900	63	3300	13560	g
Runnels	3750	1400	27900	147	2700	55340	g
Runnels	2275	1148	30250	146	4114	53160	g
Runnels	740	440	10780	26	1030	19500	g
Runnels	2600	1250	29250	100	3540	50398	g
Runnels	2060	800	19320	55	2760	36130	g
Runnels	780	312	15120	150	1670	19780	g
Runnels	1975	915	22400	35	3840	36000	g
Runnels	2340	1060	30250	350	4000	55000	g
Runnels	1540	400	13300	55	4000	32280	g
Runnels	2080	1070	30700	81	3260	52000	g
Runnels	3750	1400	27900	147	2700	55340	g
Runnels	2250	1150	24450	163	3960	40760	g
Runnels	2300	1400	28550	129	1320	54460	g
Runnels	2500	1200	22760	11	3800	42990	g
Runnels	2300	1400	28550	129	1320	54460	g
Runnels	2450	1100	29850	88	5060	51250	g
Runnels	3280	1	19540	7	2550	32320	g
Runnels	2600	1250	29250	100	3540	50398	g
Tom Green	5600	1700	37800	55	3200	80000	g
Tom Green	2575	1150	30800	460	4040	55000	g
Tom Green	2250	850	28400	153	4680	45451	g
Tom Green	3390	177	27430	560	3810	45500	g
Tom Green	4400	1170	30900	0	2280	57430	g
Tom Green	3850	6	19800	399	1840	42000	g
Tom Green	1820	800	26180	286	3000	45050	g

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a Core Laboratories, Inc., 1972
b Richter and Kreitler, 1985
c Willis, 1954
d Laxson, and others, 1960
e Price, 1978
f Aqua Science Lab, San Angelo
g Texas Railroad Commission, San Angelo

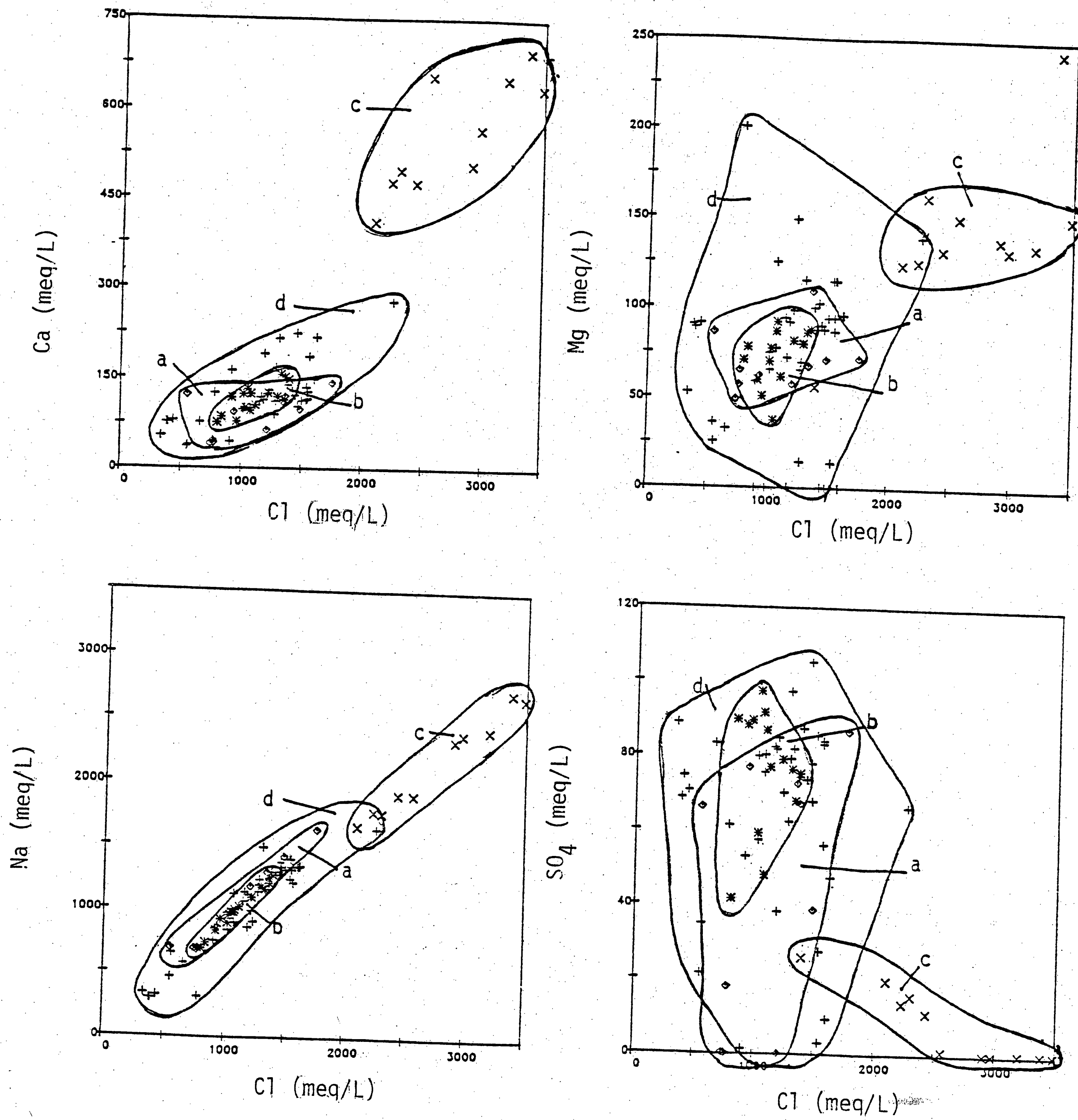

Figure 20. Plots of Ca, Mg, Na, and SO_4 versus Cl in (a) San Angelo/San Andres/Clear Fork subsurface brines, (b) in Coleman Junction brines, (c) in Canyon/Strawn and Wolfcamp brines, and (d) in brines from surface leaks and of unknown origin (see table 5).

leaky injection wells, leaky tank batteries, flowing core holes, abandoned exploration holes, and so forth, in Irion, Runnels, Concho, and Tom Green Counties generally have lower ionic concentrations than brines in Pennsylvanian units but overlap with Coleman Junction and San Angelo/San Andres/Clear fork brines (fig. 20).

Brine-Disposal Pits

Geometric means of water/oil ratios were used to estimate brine volume produced before 1969, the year unlined surface disposal pits were banned. The water/oil ratios appear to slightly increase from 1953 to 1969 (fig. 21a), as is commonly observed over the life of oil fields. According to data reported in Form W-10, water/oil ratios derived from compiled salt-water surveys lie within one standard deviation of the geometric mean ratio. The best estimate of cumulative brine production before 1969 in Tom Green and Irion Counties is 7 to 8 million bbl (fig. 21b). If spread uniformly across the two counties, the average annual production of salt water would form a 0.0004-inch-thick (0.0009-cm) layer. In comparison, natural specific discharge of ground water from the Permian Basin has been estimated at 0.43 inch/yr (1.08 cm/yr) (R. Senger, personal communication, 1987). Therefore, the volume of salt water disposed of in brine-disposal pits is much less than the volume of natural discharge. However, brine-disposal pits constitute highly saline point sources, whereas natural discharge is widespread and has much lower concentration gradients. Therefore, local impacts of brine-disposal pits may be significant.

On aerial photographs taken during 1964, 10 general areas of active, brine-filled pits were identified (fig. 22). No field check of these sites was performed,

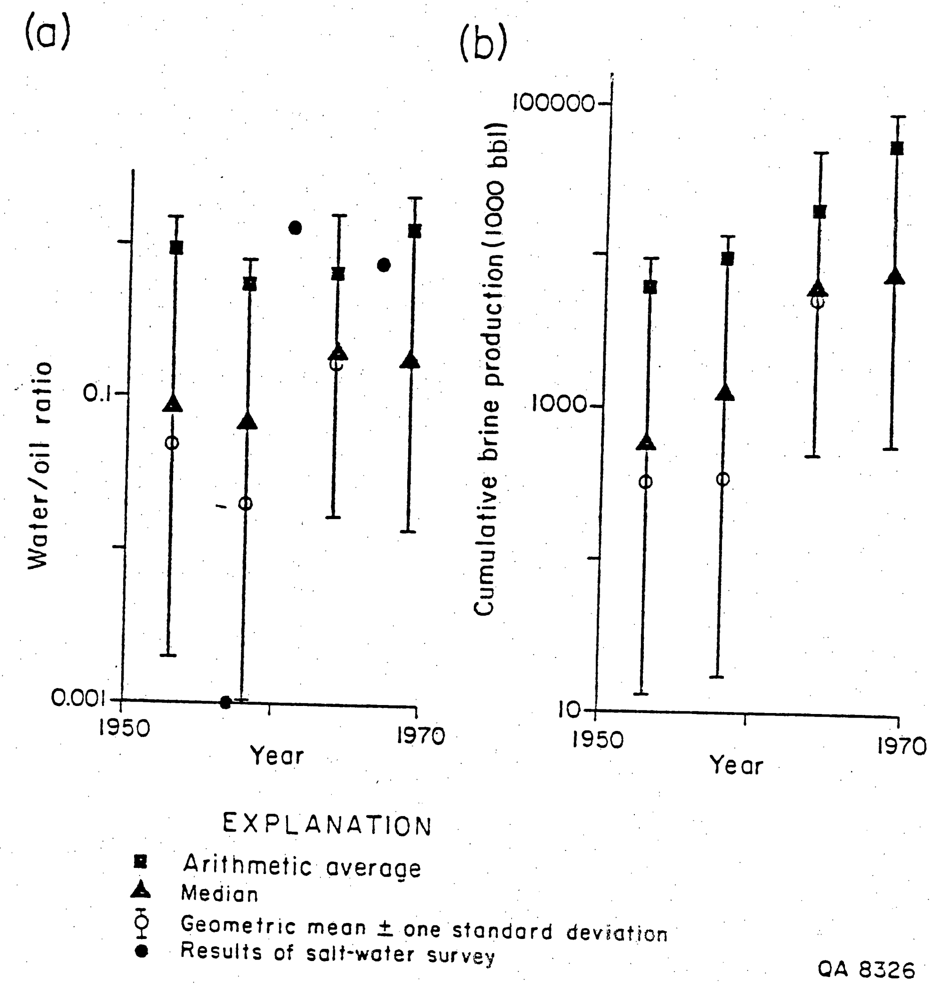

Figure 21. Estimates of (a) water/oil ratios from Form W-10 and salt-water surveys and (b) projected volume of brine produced in Tom Green and Irion Counties, derived by multiplying cumulative oil production by water/oil ratios.

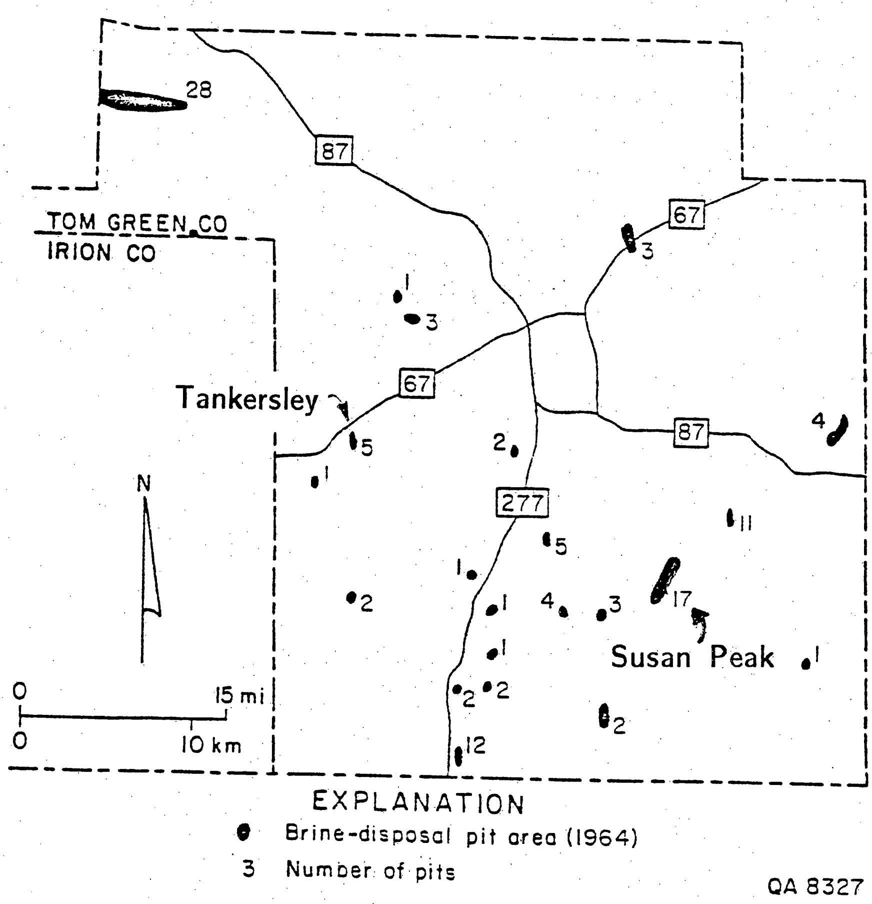

Figure 22. Active brine-disposal areas identified on photographs taken during 1964.

and these sites probably were not the only disposal sites being used at the time. Figure 22 does not show all sites of disposal pits abandoned before and after 1964, many of which are still visible because of the lack of vegetation cover.

Disposal of brine into unlined surface pits was discontinued in the late 1960's after brine contamination of shallow ground water was traced to the pits, indicating that most of the brine pumped into the pits did not evaporate. For example, Reed (1961) traced plumes of brine contamination in Mitchell and Scurry Counties, Texas, that extended from disposal pits along the direction of ground-water flow. When disposal of brine into surface pits stopped in 1969, flushing and dilution of polluted soil and ground water began near the pits.

To determine if salt water is still being flushed out and if a pollution hazard still exists owing to the amount of salt water that remains in or above shallow ground water, three abandoned brine-disposal pits were tested for soil chlorinity and chemical characteristics of shallow ground water beneath the pits.

Between 1952 and 1967 approximately 100,000 bbl of brine were deposited in up to 5 ponds in one area 2 mi (3.2 km) east of Tankersley (fig. 22). The site of the abandoned pits is now covered by vegetation, but drilling at this site revealed evidence of previous brine disposal. An oily smell was noticed in the upper 3 ft (1 m) below land surface, and ground water at the water table at a depth of 46 ft (14 m) was highly mineralized (Cl=20,750 mg/L) (no. 9, table 3). Chloride concentrations in soil samples were highest from 5 ft to 10 ft (1.5 to 3 m) below land surface and lowest at the water table (fig. 23). Salt water also seeped into a test well at a depth of 24 ft (7 m) in an abandoned disposal pit in Susan Peak Field, southeast Tom Green County (fig. 24). The amount of water from the seep and salinity (Cl=13,070 mg/L) of the water (no. 24, table 3) were lower than

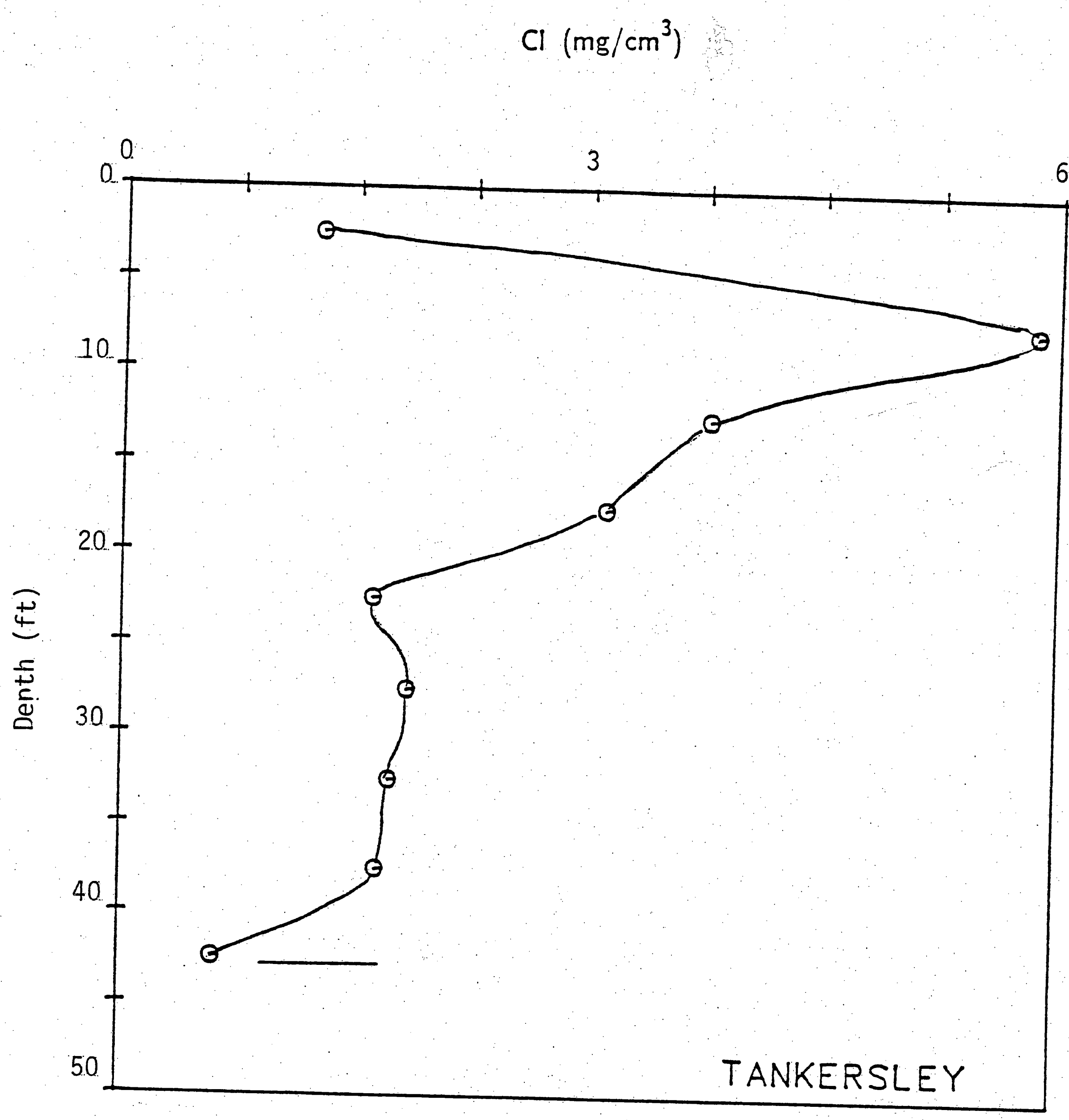

Figure 23. Chloride concentration in soil underlying abandoned brine-disposal pit no. 9 near Tankersley (see figs. 10 and 22). Bar indicates water table at a depth of 46 ft (14 m).

those at the test well in the pit near Tankersley The chloride profile with depth indicates that chloride concentrations in the soils are smaller at the Susan Peak site and peak in chloride concentration at the depth of the seep rather than near land surface (fig. 24). At the Tankersley site, chloride concentrations were lowest at the water table. This suggests that brine at the Tankersley abandoned pit has been diluted and flushed from the soil. The water sample obtained at the Susan Peak abandoned pit seems to be percolating downward more slowly through the carbonate rock matrix. No water was encountered during drilling at a second abandoned brine-disposal site in the Susan Peak Field (fig. 24b). Soil chlorinity at the second site was much smaller than at the other disposal pits (fig. 24). The total amount of brine pumped into surface ponds and the duration of disposal-pit operation at any of the Susan Peak Field leases are unknown.

Abandoned Deep Exploration Holes

Pathways for upward movement of salt water into shallow aquifers occur in old, deep exploration wells that were not plugged or were inadequately plugged by present standards. These wells include those drilled for water and hydrocarbons. Marshall (1976) reported that during the severe drought in 1953 many water wells west of San Angelo were drilled to depths of 500 ft (150 m) and that after salt water was encountered many of those holes were abandoned but not plugged. Locations of these wells were not given by Marshall (1976). A search among hundreds of drillers' logs of water wells in western Tom Green County did not confirm that water exploration wells were commonly drilled deep and that salt water was encountered. Local water-well drillers and the representative of a well-service business, all having decades of experience in the study area, could recall

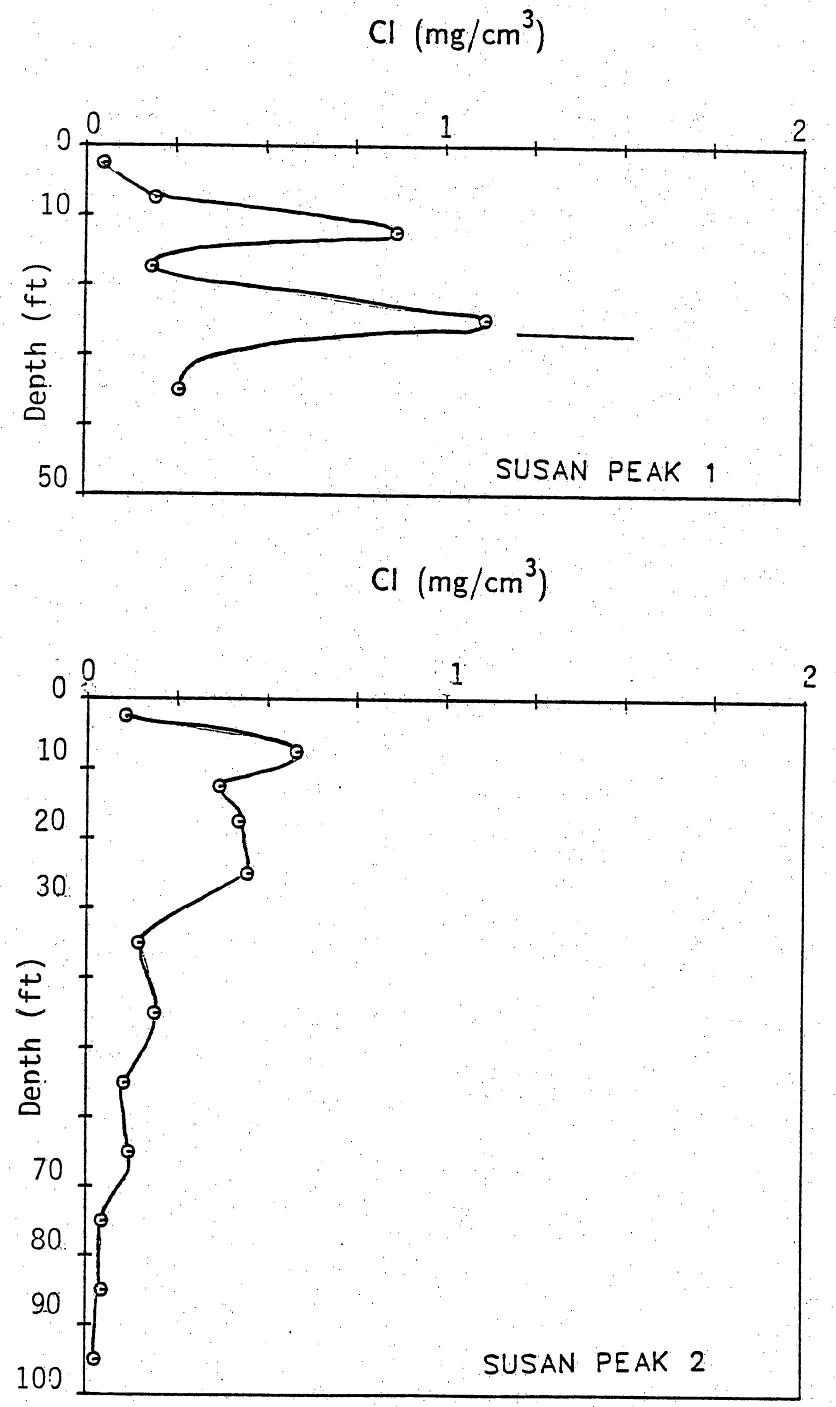

Figure 24. Chloride concentration in soil underlying abandoned brine-disposal pits no. 24a and no. 24b in the Susan Peak Field (see figs. 10 and 22). Bar indicates water table at a depth of 24 ft (7.3 m).

only a few such deep drillings. Specific deep water wells could not be located. Therefore, in the following discussion of deep holes, only those holes that were drilled for exploration of oil and gas resources are considered.

In Tom Green County, more than 1,000 deep oil exploration wells have been drilled and abandoned because no oil or gas was found (fig. 25). Many of these wells were drilled and abandoned before regulations for drilling and plugging to protect water resources were implemented. Brine contamination from inadequately plugged holes can be extensive where it remains undetected. For example, Reed (1961), mapped the extent of salt-water pollution caused by an unplugged dry hole that leaked brine into shallow ground water for 22 years. Ground water beneath an estimated 400 to 600 acres (1.6 to 2.4 km^2) of land had been affected by salt water from this hole (Reed, 1961).

Excluding areas where Cretaceous rocks overlie older strata (fig. 1), required depths of surface casing (established by Texas Department of Water Resources) vary between 150 ft (45 m) and 350 ft (105 m) below land surface. Brine flow from the overpressured Coleman Junction Formation from other brine-bearing formations to land surface is possible where an artificial pathway is provided. Therefore, correct depths of cement plugs and surface casing in abandoned holes are important for protecting ground-water resources.

To test for possible leakage of brine from an abandoned exploration borehole, a hole having a shallow surface-casing depth and no plug was selected between the Coleman Junction Formation and the base of surface casing, according to plugging report no. 53 (appendix 3, figs. 11 and 26). The hole had been drilled to a depth of 6,212 ft (1,890 m) in 1955 and was plugged within 30 days after drilling was completed. The reported plugging consisted of one plug made of 5

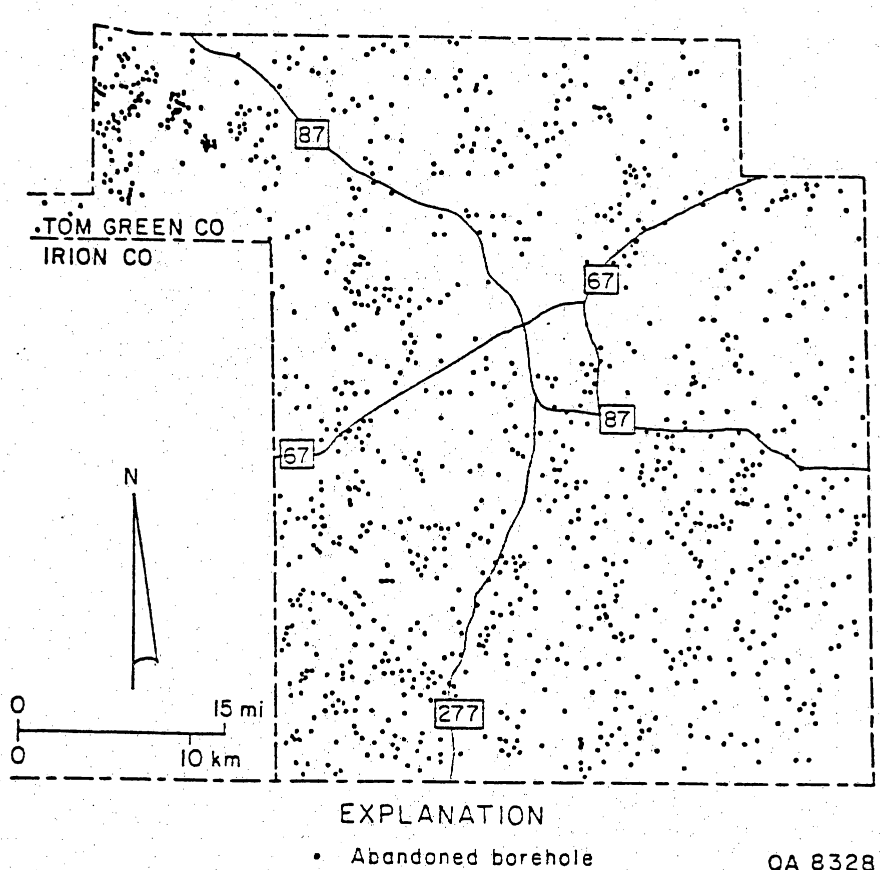

Figure 25. Location of abandoned exploration boreholes for oil and gas in Tom Green County.

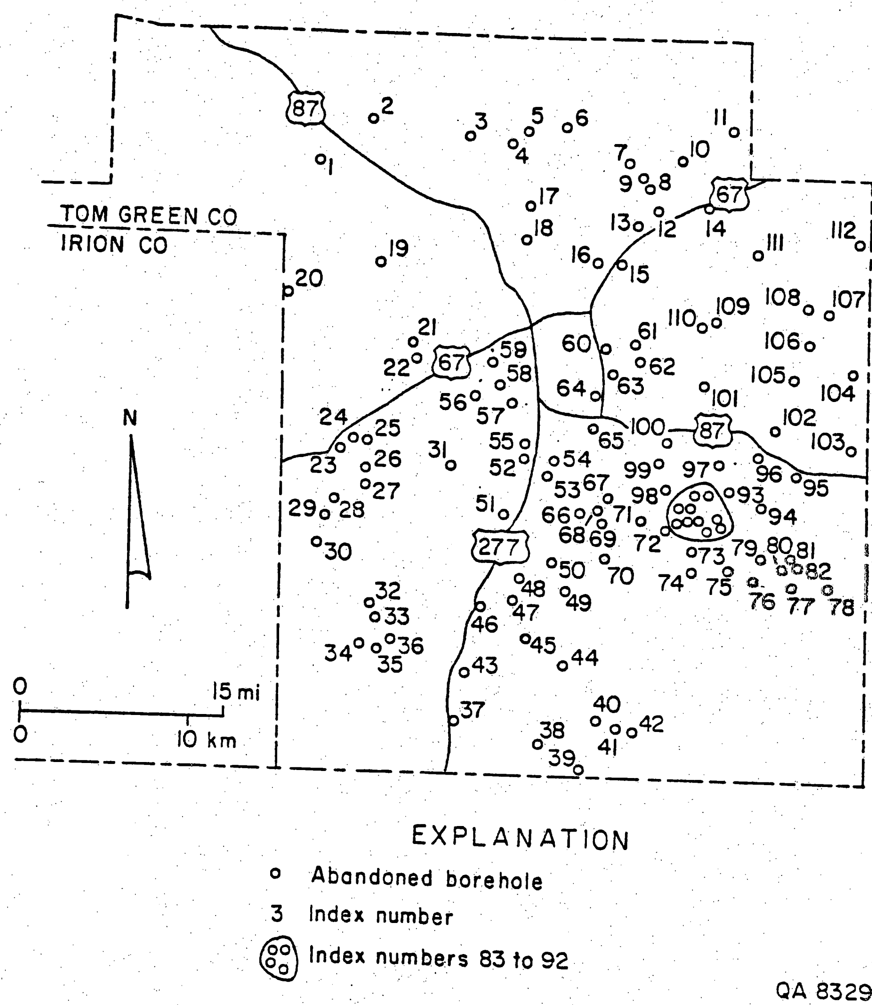

Figure 26. Location of abandoned exploration boreholes with plugging reports that were inventoried during this study (appendix 3).

sacks of cement at the top of the well, a second plug made of 5 sacks at the base of surface casing at a 100-ft (30-m) depth, and two plugs made of 20 sacks of cement each at 4,880-ft (1,490-m) and 5,190-ft (1,580-m) depths (fig. 27a). Drilling mud stood in the hole from 1 ft (0.3 m) below the capped wellhead to 90 ft (27 m) below the top of surface casing (fig. 27b), at which depth a 30-ft (9-m) plug was found. Drilling mud and water were then bailed from the borehole to lower water level to 140 ft (42 m) below land surface. Within 30 minutes, hydrogen-sulfide brine began to flow at land surface from the borehole at a rate of 8 gal/min (0.5 L/sec) at a surface pressure of greater than 60 psi (414 kPa). Chloride concentration in a sample (no. 22, table 3) obtained after mud was bailed from the well and the flowing water clarified was 29,160 mg/L. To check for possible leakage of brine from this abandoned borehole, a 160-ft-deep (48-m) test hole was drilled approximately 150 ft (45 m) north and down gradient of the brine well (fig. 27d). No major water-bearing units were encountered during drilling, but a seep was detected at approximately 127 ft (38 m) below land surface. After 24 hours, 35 ft (10 m) of water had collected in the borehole from this seep. The water sample (no. 21, table 3) was a hydrogen-sulfide brine with a lower chloride concentration (19,380 mg/L) than that in the adjacent abandoned borehole. Sample nos. 21 and 22 plot at identical concentration percentages of major cations and major anions in a Piper plot (fig. 11), indicating that they are the same water type. Concentration ratios of major anions and cations for the two samples indicate that sample no. 21 resulted from dilution of sample no. 22; the ratio of brine to diluting water was approximately 3:2. Concentrations of bicarbonate and bromide do not follow this dilution trend.

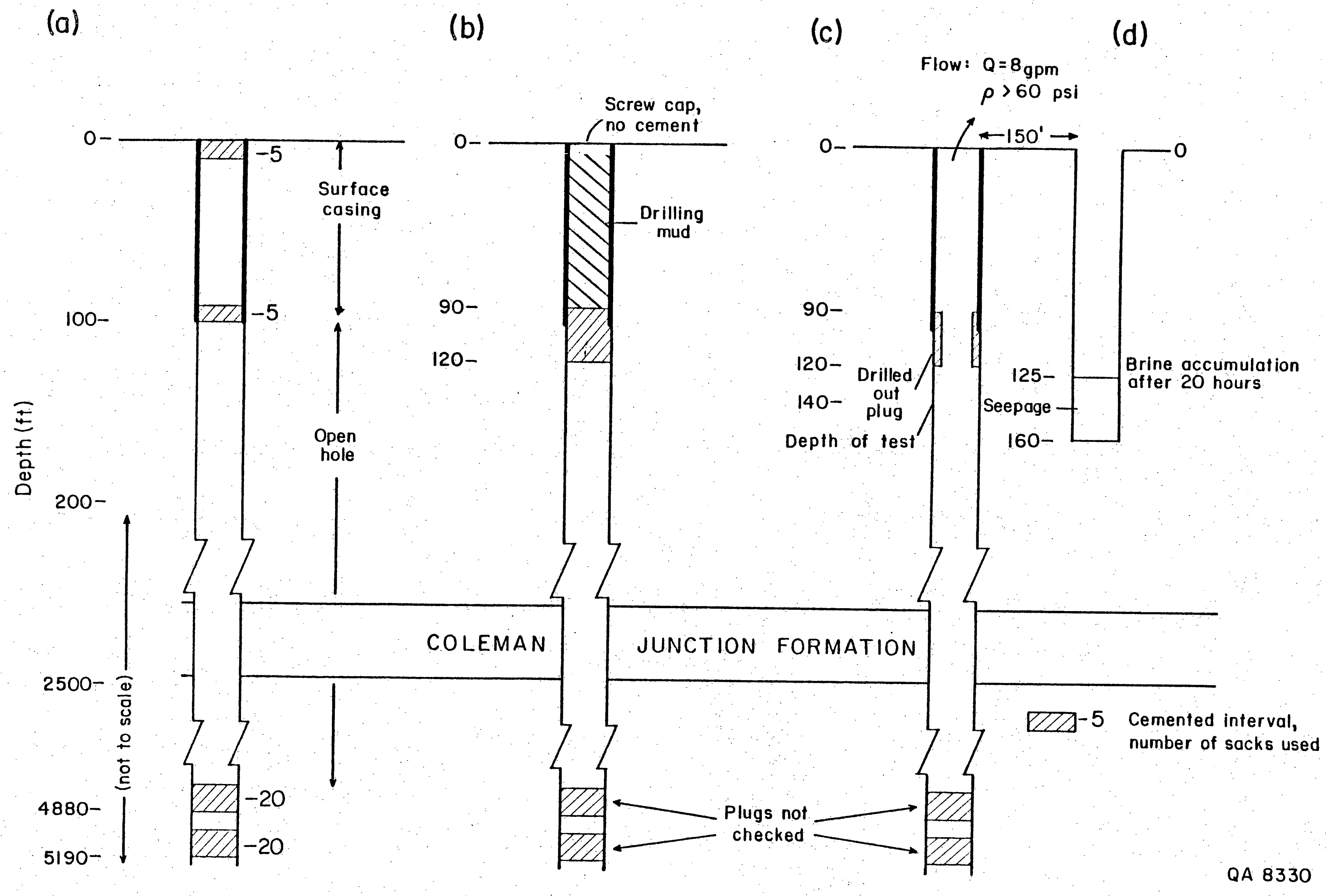

Figure 27. Schematic diagram of abandoned borehole no. 22 and test well no. 21, Washington County School Land lease. (a) Condition according to plugging report. (b) Actual condition of abandoned hole. (c) Testing of abandoned hole. (d) Shallow test hole no. 21 drilled 150 ft (45 m) away from abandoned borehole (borehole 22 of table 3 is identical with abandoned borehole 53 of appendix 3).

DISCUSSION

Hydrochemical Facies and Salinity

Ca-HCO_3 hydrochemical facies (fig. 8a) most likely originates from reaction of recharging water with calcite ($CaCO_3$) and dolomite [$CaMg(CO_3)_2$] in Cretaceous carbonate rocks beneath plateaus that flank the Concho River valley. Na-HCO_3 and mixed-cation-HCO_3 hydrochemical facies (fig. 8b) develop as ground water flows through Cretaceous rock toward discharge areas in the Concho River valley (fig. 9). The change from Ca-HCO_3 facies to Na-HCO_3 and mixed-cation-HCO_3 facies is probably due to ionic exchange of dissolved calcium for sodium adsorbed on clays that are disseminated within the limestones and form partings between limestone beds. Solution of dolomite continues along the flow path and most likely accounts for the increased magnesium concentration.

Na-Cl (fig. 8d) and Ca-SO_4 (fig. 8c) hydrochemical facies coincide with Permian formations beneath the Concho River valley and probably reflect discharge of the naturally occurring saline ground water that flows eastward within Permian rocks across West Texas. The mixed-ion composition of ground water prevalent in Concho River valley alluvium (figs. 8f and 9) may originate from mixing of (1) ground water that is discharged from Permian and Cretaceous formations and (2) ground water that is locally recharged to the alluvium from precipitation, irrigation, and seepage from rivers and streams. Lee (1986) hypothesized that the salinity increase during the early 1950's was caused by recharge from evaporatively concentrated irrigation water. Overproduction of ground water for irrigation during the drought of the early 1950's also might have decreased hydraulic head in shallow aquifers and increased the amount of subsurface brine that discharged from the regional flow system and mixed with shallow ground water.

Locally occurring Na-Cl, $Ca-SO_4$, Ca-mixed-anion, and Na-mixed-anion hydrochemical facies have an anomalous distribution within regionally defined hydrochemical facies (fig. 9). Some of these samples probably reflect point-source contamination of ground water; other samples probably were collected from deep wells that tapped an aquifer other than the principal one in a given area.

Anomalous Chemical Composition and Definition of Brine Source

Among all samples, irrespective of hydrochemical facies, chloride concentration is closely correlated with sodium concentration (fig. 28), indicating that most ground water in the study area has been influenced by varying amounts of Na-Cl water. Subsurface brines collected during this study form an end member of the Na-Cl trend. The geographically anomalous samples of Na-Cl, $Ca-SO_4$, and mixed-anion hydrochemical facies that were previously mentioned are intermediate in salinity between fresh-water samples and subsurface brines.

Ratios of Cl/SO_4 versus SO_4 ions are inversely related among subsurface brine samples (fig. 29); as is commonly observed, sulfate concentrations are low in brines with the highest chlorinity. A similar inverse trend exists among all ground-water samples from aquifers in the study area; although there is considerable scatter, the negative slope of the shallow ground-water data is statistically significant. The San Andres/San Angelo/Clear Fork and Coleman Junction brine end member in the Cl/SO_4 versus SO_4 plot is similar to shallow ground water with the highest SO_4 concentrations and lowest Cl/SO_4 ratios and is also similar to some of the anomalous Na-Cl, $Ca-SO_4$, and mixed-anion hydrochemical facies.

A plot of Cl/SO_4 versus Na/Ca ratios of ions in the shallow ground waters (fig. 30) shows a positive slope that reflects the influence of Na-Cl facies (fig. 29).

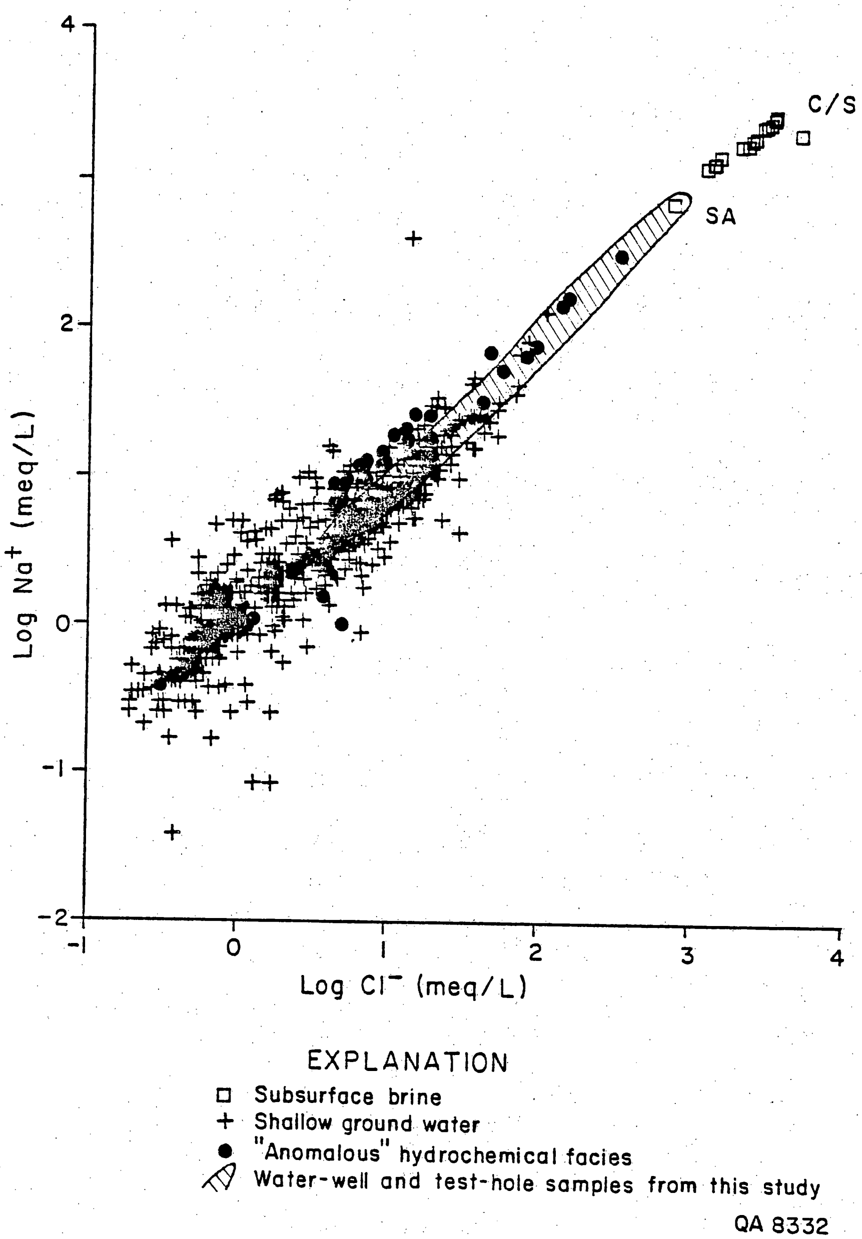

Figure 28. Variation in dissolved sodium and chloride in shallow ground waters and subsurface brines in Tom Green and eastern Irion Counties. Geographically anomalous samples of Na-Cl and Ca-SO_4 hydrochemical facies plot between shallow ground water and subsurface brines. Water-well and test-hole samples collected during this study also plot close to shallow subsurface brines from these brine units. Brine end members marked by: SA - San Andres/San Angelo/Clear Fork, C/S - Canyon/Strawn, and W - Wolfcamp.

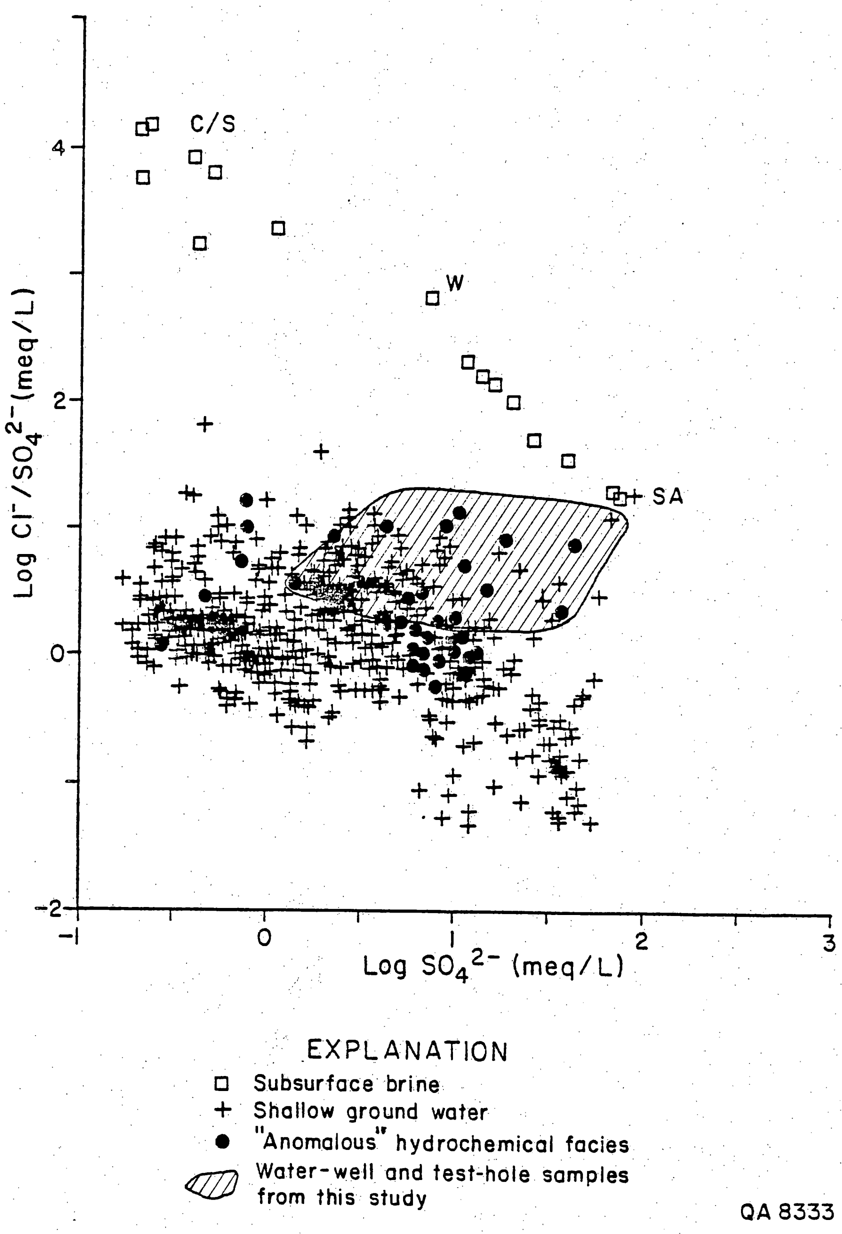

Figure 29. Variation in Cl/SO_4 ratio with SO_4 concentration in shallow ground waters and oil field brines in Tom Green and eastern Irion Counties. Anomalous samples of Na-Cl and $Ca\text{-}SO_4$ hydrochemical facies in shallow ground water are marked by solid circles. Brine end members as identified in figure 28.

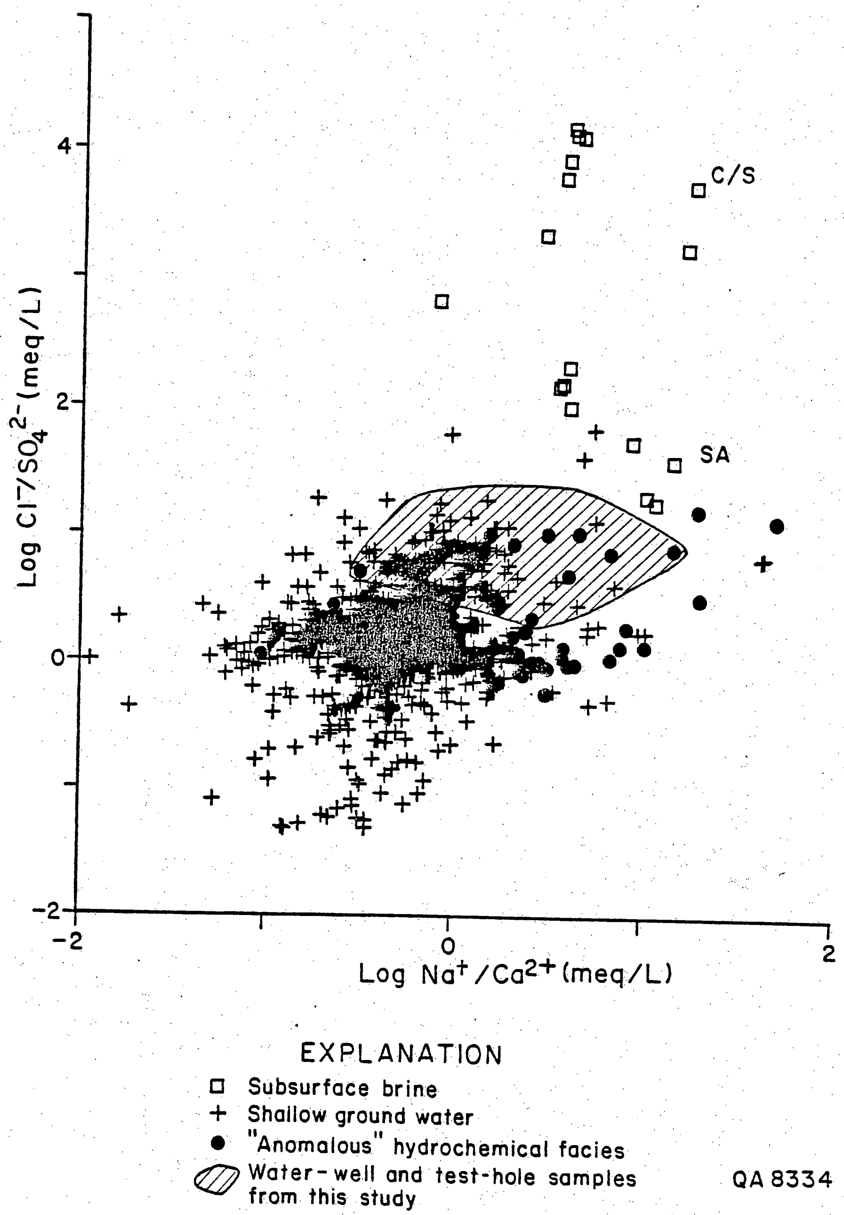

Figure 30. Variation in Cl/SO_4 and Na/Ca ratios in shallow ground waters and oil field brines in Tom Green and eastern Irion Counties. Brine end members as identified in figure 28. Anomalous samples of Na-Cl and $Ca\text{-}SO_4$ hydrochemical facies in shallow ground water are marked by solid circles.

Samples of anomalous Na-Cl and Ca-SO_4 waters from shallow aquifers again are more similar to the San Andres/San Angelo/Clear fork end member of subsurface brines than to the Canyon/Strawn end member. The same association of shallow ground water and the San Angelo/San Andres/Clear fork end member is shown by plotting Br/Cl ratios versus Cl (fig. 16). Low Br/Cl ratios in high-Cl ground waters seem to eliminate Pennsylvanian brines as possible salt-water sources for mixtures with shallow ground water. The similarity between the most saline shallow ground water, ground water with geographically anomalous hydrochemical facies, and the San Andres/San Angelo/ Clear Fork end member of subsurface brines that is shown on many different plots (figs. 16 and 28 through 30) suggests that anomalous waters result from discharge of brines from the San Angelo/San Andres/Clear Fork or the Coleman Junction units into shallow ground water.

Investigation of Salinization Mechanisms

Waters were previously defined as anomalous based on their geographic distribution within regionally prevalent hydrochemical facies. This includes samples with high and low chloride concentrations. Mixing of subsurface brine with shallow ground water and sources of brine can be detected most readily at high chloride concentrations (Richter and Kreitler, 1985). Therefore, shallow ground waters with chloride concentrations higher than average were sampled to investigate salinization mechanisms.

Water samples from wells and test holes are intermediate between low-Cl shallow ground water and subsurface brines in all the preceding plots: Na versus Cl (fig. 28) and Cl/SO_4 versus SO_4 (fig. 29) and ratios of Na/Ca (fig 30).

Therefore, waters with high chlorinity follow the trend of samples with anomalous hydrochemical facies and are more similar to subsurface brines from the San Angelo/San Andres/Clear Fork end member and to brines from the Coleman Junction Formation than to brines from Pennsylvanian units. The low Br/Cl ratio of the saline samples (fig. 16) also supports this association. But because San Angelo/San Andres/Clear Fork brines and brines from the Coleman Junction Formation (fig. 20) are not readily distinguishable, it is impossible to identify a brine source within Leonardian or Guadalupian units (table 1) or to determine the dominant mixing mechanism responsible for high-saline ground waters in Tom Green County. Possible mixing mechanisms are (1) natural discharge of salt water from the San Angelo, San Andres, and Clear Fork units in western Tom Green County, (2) discharge of the same units through unplugged water wells that were drilled into saline portions of these units, (3) discharge of Coleman Junction brine through insufficiently plugged deep holes, and (4) continued leakage of salt water from soils into shallow ground water under sites of former brine disposal. These mixing mechanisms are discussed in the following sections.

Deep Water Wells

Deep water wells probably are not major contributors to salt-water problems in Tom Green County. No written records of such deep wells exist, and on the basis of informal surveys of well drillers, it can be assumed that the actual number of wells is relatively small. Where they occur, unplugged deep water wells may pose a local salinization hazard.

Natural Discharge of Salt Water from San Angelo Formation

Two test holes were drilled into the San Angelo Formation to test the natural salinity of its ground water. All three samples were saline with chloride concentrations ranging from 5,280 mg/L to greater than 30,000 mg/L, and hydraulic head was high enough for salt water to flow to land surface from one of the test holes. Willis (1954) reported a similar saline water with a chloride concentration of 29,500 mg/L from a 122-ft-deep (37-m) well approximately 2.5 mi (4 km) southwest of test hole no. 5 (fig. 10). The 1948 collection date of this sample preceded oil exploration drilling in the area. Therefore, it can be assumed that samples collected from test hole no. 5 and the sample reported by Willis (1954) are representative of shallow saline ground water from the San Angelo Formation, that salt water in the San Angelo Formation at shallow depths tends to be naturally saline, and that the San Angelo Formation could be a major contributor to the salinity of shallow ground water.

Abandoned Brine-Disposal Pits

High-salinity ground water was encountered at shallow depths in two of three tested abandoned brine-disposal pits. The total mass of chloride in storage beneath abandoned pits can be estimated from average soil chlorinity and average pit size. Chloride concentrations in soil underlying pit no. 9 near Tankersley vary from 0.6 mg/cm^3 at depths from 40 to 45 ft (12 to 13.5 m) to 5.8 mg/cm^3 at depths of 5 to 10 ft (1.5 to 3 m) (table 6; fig. 23). In contrast, chloride content of soil in the upper 20 ft (6 m) of test hole no. 7 outside the pit area is only 0.007 mg/cm^3 (table 6). At an average chloride content of 2.4 mg/cm^3 (table 6) of soil and a size for the former five ponds of approximately 120 ft x 180 ft (36 x

Table 6. Chloride concentration in soils under abandoned brine-disposal pits.

Location	Depth Interval (ft)	Chloride (mg/cm^3)	
Tankersley	0-5	1.26	
	5-10	5.86	
	10-15	3.77	
	15-20	3.11	
	20-25	1.62	
	25-30	1.85	
	30-35	1.74	
	35-40	1.66	
	40-45	0.61	(Water)
Susan Peak #1	0-5	0.05	
	5-10	0.19	
	10-15	0.86	
	15-20	0.18	
	20-30	1.12	(Seep)
	30-40	0.26	
Susan Peak #2	0-5	0.11	
	5-10	0.58	
	10-15	0.34	
	15-20	0.42	
	20-30	0.44	
	30-40	0.14	
	40-50	0.19	
	50-60	0.10	
	60-70	0.12	
	70-80	0.04	
	80-90	0.04	
	90-100	0.03	

55 m), there is an estimated 66 metric tons of chloride in the soil beneath the five abandoned pits and above water table at a water depth of 45 ft (14 m). This is approximately 4% of the total amount of dissolved chloride (approximately 1,500 metric tons in 100,000 bbl of brine from Pennsylvanian reservoirs) that was pumped into disposal ponds in this area between 1952 and 1967. However, the 66 metric tons represent a significant, long-term salinization potential. Assuming the ground-water recharge rate is 1 inch/yr (2.5 cm/yr) (recharge estimates for the Texas High Plains range from 0.5 to 1.6 inches/yr; R. Nativ, personal communication, 1987) and assuming that chloride is leached from the soil to produce salt water with a constant Cl concentration of 20,000 mg/L (as in sample no. 9), it would take more than 60 years to reduce chloride concentrations in the soil to the levels measured in soil away from the abandoned disposal pits.

Present chloride concentrations in soils under former disposal pits are not always as high as those beneath the Tankersley pits. For example, maximum concentrations of 0.7 and 1.3 mg/cm^3 were measured in soil samples from two disposal pits at the Susan Peak Field in southeastern Tom Green County (table 6, fig. 24). However, chloride content of one seep sample (no. 24, table 4) obtained at a shallow depth was high. The Susan Peak brine-disposal pits that were tested appear to be inactive in aerial photographs taken in 1964. Many brine-disposal ponds existed in the Susan Peak Field, but duration of brine disposal and the amount of brine pumped into tested pits are unknown. It is possible that less brine volume was disposed into the Susan Peak Field pits than into Tankersley pits, which could explain the differences in soil chlorinity.

In the Tankersley area, leakage of salt water from the soil underlying the former pits into shallow ground water may have spread a considerable distance.

Sample no. 9 obtained in a conglomerate bed at 46 ft (14 m) directly below the pit floor, had a chloride concentration of 20,750 mg/L. A water sample (no. 10, table 3) from a 40-ft-deep (12 m) hole drilled approximately 0.5 mi (0.8 km) east of test hole no. 9 had a chloride concentration of 12,190 mg/L; this sample was obtained from a gravel bed at 24 ft below land surface. In plots of Ca, Mg, Na, and SO_4 versus chloride (fig. 31), sample no. 10 lies intermediate between sample no. 9 and samples obtained from test hole no. 7, which was drilled approximately 300 ft (90 m) west of the Tankersley pit no. 9. Because ground-water flow in this area is from west to east (Lee, 1986), transport of salt water from the former pits is mainly toward the east. Along the flow path, salinity of the salt water contaminant plume decreases as the salt water spreads out and becomes diluted. Samples from test hole no. 7 are less affected by this spread because test hole no. 7 is located up gradient (300 ft [90 m]) from the abandoned pits.

In 1978, the District Office of the Railroad Commission of Texas analyzed water samples from 21 water wells located between Tankersley and Twin Buttes Reservoir. In plots of Ca, Mg, Na, and SO_4 versus Cl, the trend of these samples consistently differs from the trend defined by sample nos. 7, 9, and 10 (fig. 31). Therefore, sample nos. 7, 9, and 10 are anomalous for this area. Leaching of salt from beneath abandoned disposal pits might account for this anomalous water composition. Richter and Kreitler (1985) concluded that the high salinity of a water sample (their no. 39) from a well approximately 1,000 ft (300 m) south of the abandoned brine-disposal pit no. 9 most likely resulted from the mixing of shallow ground water and subsurface brine. Four additional samples from this well were obtained by the Railroad Commission of Texas in 1985 following the Richter and Kreitler (1985) report. Chemical composition of these samples does not follow the trend indicated by other water samples but does fit the trend defined by

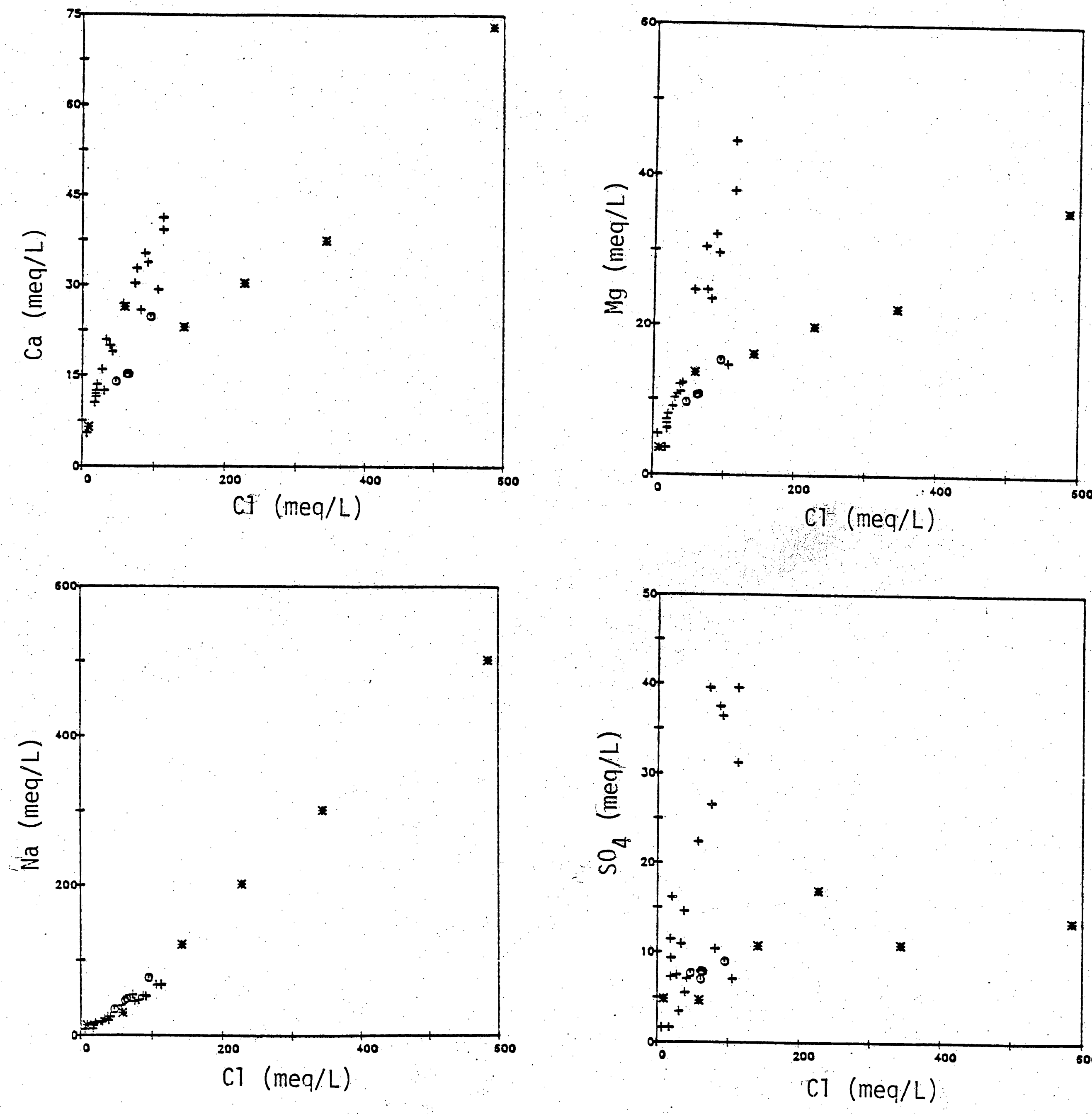

Figure 31. Plots of Ca, Mg, Na, and SO_4 concentrations versus Cl in shallow ground water in the Tankersley area. Data sources are: + - Railroad Commission of Texas records; o - well no. 39 (Richter and Kreitler, 1985); and * - test holes 7, 9, and 10.

sample nos. 7, 9, and 10 (fig. 31). This would indicate that the subsurface brine that affected ground-water composition at well no. 39 possibly derived from leaching of salt from the abandoned brine-disposal pit.

Abandoned Exploration Holes

Abandoned dry holes provide a pathway for subsurface brine to contaminate shallow ground-water where surface-casing depth and location of plugs are inadequate to prevent brine discharge. Cases of brine flow at land surface and contamination of shallow ground water have been investigated by the Railroad Commission of Texas; 11 wells were reentered and plugged in Tom Green County during 1984 to 1987. Some exploration holes had never been plugged. Other boreholes had inadequate plugs. At test hole no. 22 (current study), brine leaked from the uncased section of the hole into test hole no. 21, 150 ft (45 m) away (fig. 27).

Similar conditions may exist in other deep exploration boreholes that were abandoned more than 25 years ago. Abandoned boreholes that possibly allow Coleman Junction brine to flow upward into permeable units at shallow depths appear to be most concentrated in southeastern Tom Green County (fig. 26). Test drilling was performed in this area to detect possible brine leakage from abandoned exploration boreholes. Current regulations specify that surface casings extend to depths from 150 to 350 ft (60 to 105 m) below land surface, which reflects the approximate depth to the base of fresh water in this area. In 1985, the Railroad Commission of Texas at San Angelo studied abandoned exploration holes in the area after a ground water was encountered with an unusually high chloride concentration of 4,676 mg/L at a depth of 75 ft (23 m). An abandoned exploration hole (no. 90, app. 3) with surface casing extending to a 240-ft (73-m) depth and a reported cement plug at depths of 204 to 248 ft (62 to 75 m), was suspected as the source of salt water approximately 1 mi (1.6 km) south of the contaminated well. The abandoned hole was reentered and replugged by the Railroad Commission of Texas. During the present study, an identical saline water (Cl=4,450 mg/L) was obtained at 75 ft (23 m) from test hole no. 23, drilled at the site of the contaminated and plugged water well. This suggests that brine is still moving through the shallow subsurface in this area. Among several holes that could allow brine leakage from the Coleman Junction Formation in this area, hole no. 88 (fig. 26; app. 3) may be the source, considering its proximity to test hole no. 23 and the shallow depth of its surface casing (170 ft [52 m]) and to reported plugging (25 sacks of cement at 195 ft [60 m]) when compared to the depth of the base of fresh water (250 to 325 ft [75 to 97 m], established by TDWR) in that area.

CONCLUSIONS

Natural movement of salt water from the San Angelo, San Andres and Clear fork units into the shallow subsurface of western Tom Green County seems to be responsible for the regionally poor quality of shallow ground water. Brine flow from deep and overpressured formations upwards via insufficiently plugged exploration holes can affect large areas where many such wells exist. Similarly, contamination of water resources by leaching of salts from beneath abandoned brine-disposal pits can affect areas where large amounts of brine were disposed. These three salt-water sources affect shallow ground-water quality in parts of Tom Green County, Texas. The chemical composition of the likely sources of salt water are similar; the similarity prevents the distinction of salt-water sources for most cases of pollution. Therefore, contamination from natural and man-made sources can be separated only by deductions based on the natural hydrogeological settings and historical records of drilling activities and brine disposal.

Poor-quality ground waters in shallow aquifers in Tom Green and eastern Irion Counties, Texas, are chemically most similar to subsurface brines from the San Andres, San Angelo, and Clear Fork units. The subsurface brines are moving eastward along regional flow paths and are discharging into shallow aquifer systems in western Tom Green County. Evidence for discharge of brine from regional flow systems of the Permian Basin include: (1) potentiometric gradient in brine-bearing formations showing eastward flow toward formation outcrops, (2) prevalence of subsurface brine just tens of miles west of outcrops, (3) excellent correlation of Na and Cl ionic concentrations among all samples, (4) association of Na-Cl and Ca-SO_4 hydrochemical facies with outcrops and subcrops of Permian formations, (5) chemical similarity between subsurface brines and shallow ground water, and (6) artesian fluid potentials of these formations in test hole no. 5.

Brines from the Coleman Junction Formation flow from the deep subsurface into shallow aquifer units through inadequately plugged boreholes. Discharge of brine from the Coleman Junction Formation is expected for the following reasons. (1) Artesian fluid potentials in this brine-bearing unit are higher than those in overlying units and are near or at land surface. (2) Brine seeped from abandoned hole no. 22 into test hole no. 21. (3) Over the past decades, several cases of brine flowing at land surface from abandoned holes in Tom Green, Concho, and Runnels Counties were reported and were attributed to flow communication between the holes and the Coleman Junction aquifer.

Leaching of salt from soils underlying abandoned brine-disposal ponds is an ongoing process two decades after this disposal method was discontinued.

Differences in salinity of soil and ground water under abandoned disposal pits are probably associated with the history of brine disposal at each site.

The existence of deep water wells that possibly allow upward flow of saline water into better quality zones could not be documented. Regionally, the potential for contamination from the few reported water wells probably does not play a significant role realtive to the other salinity sources.

Hydrochemical facies and Br/Cl, Cl/SO_4 and Na/Ca ratios used together help distinguish where shallow ground waters are influenced by subsurface brine being discharged from the Permian Basin regional ground-water flow system. However, because the brines in the San Angelo, San Andres, and Clear Fork units are chemically similar to brines in the Coleman Junction Formation, it is not always possible to distinguish between natural salinity and artificial contamination of shallow ground water. In western Tom Green County, natural mixtures of shallow ground water and discharging San Angelo, San Andres, and Clear Fork brines cannot be separated from mixtures of shallow ground water and Coleman Junction brine moving upward in inadequately plugged well bores. In eastern Tom Green County, where Clear Fork formations crop out, brines are not known to occur, but the Permian formations do have distinct hydrochemical facies. Instances of high salinity in shallow ground water in eastern Tom Green County most likely are associated with inflow of brine from the Coleman Junction Formation.

Chemical and isotopic analyses of shallow ground waters and subsurface brines included some constituents that proved useful for this study and others that did not meet expectations. In this study, plots of major chemical constituents such as Ca, Mg, Na, SO_4 and Cl and plots of Na/Cl, Na/Ca, and Cl/SO_4 ratios were the most useful tools used to distinguish between brines and to distinguish salt water leached from beneath abandoned brine-disposal pits from other types of salt water.

Low Br/Cl ratios in chloride-rich ground water indicate mixing between shallow ground water and subsurface brines from San Andres, San Angelo, and Clear Fork units. Information gained from oxygen ($\delta^{18}O$), hydrogen (H^2), carbon ($\delta^{13}C$), and sulfur ($\delta^{34}S$) isotopes was similar to information gained from major ions; therefore, routine measurements in salinity investigations of this kind is not justified. The difference in concentrations of organic acids (acetate and propionate) between brines in Pennsylvanian versus San Angelo, San Andres, and Clear Fork units allows another basis for distinction. However, because the aliphatic acid anions are dilute in the subsurface brines at shallow depths and might be destroyed by bacteria in shallow aquifers, these constituents probably cannot be used to recognize sources of salinization.

RECOMMENDATIONS

This program field tested three hypotheses on the sources of brine. Detailed testing of any one source, however, was not possible. Two areas that need additional work are the contamination potential from abandoned brine-disposal pits and the effectiveness of plugs set at different depths in a borehole in preventing brine migration to potable ground-water supplies.

To assess contamination of water resources by abandoned disposal pits, an inventory and mapping of all former sites of brine disposal is needed. Many former disposal sites can still be recognized (1) from aerial photographs, (2) in the field from a lack of vegetation cover, and (3) from questionnaires sent to operators of oil wells. Test drilling and geophysical investigations at additional sites to trace the extent of salt-water plumes moving from those sites by more detailed monitoring will help to quantify salinization hazards associated with abandoned brine-disposal pits. Abandoned disposal pits that were previously investigated should be tested first to determine how rapidly salinity associated with the salt-water plumes is changing.

The effectiveness of plugs set at different depths needs to be investigated. Cement plugs are generally set at the base of fresh water. Surface casing is also set from land surface to the base of fresh water. In Tom Green County, plugs have also been set at the top of the Coleman Junction Formation. The importance of these Coleman Junction plugs is unknown. There are brine-bearing formations above the Coleman Junction that would be unaffected by this plug. Wells with plugs at different depths need to be monitored. A well with just a plug at the base of fresh water should be monitored, and a well with an additional Coleman Junction plug should be monitored to determine which approach effectively prevents brine migration.

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Appendix 1. Chemical composition of shallow ground water in Tom Green and eastern Irion Counties.

Lat. (utm)	Long. (utm)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	pH	Sample date	Formation*	Sample depth (ft)	Land elevation (ft)	A	B
3505843.9	438173.3	68	48	31	-	403	66	27	-	-	09/12/40	-	87	2210	13	1
3506306.2	443916.8	69	31	7	-	348	-	15	-	-	12/03/40	-	63	2150	1	1
3501094.0	445663.2	56	33	4	-	305	14	13	-	-	12/04/40	-	39	2055	13	1
3501007.6	446176.5	107	44	38	-	384	46	100	32.0	-	10/01/40	-	60	2070	1	1
3500468.6	446218.3	76	40	25	-	329	50	45	28.0	-	12/02/40	-	60	2060	13	1
3500425.5	444433.7	66	34	11	-	354	16	16	-	-	12/02/40	-	60	2090	1	1
3501568.5	443595.4	120	72	153	-	336	421	150	-	-	11/29/40	-	140	2115	16	1
3501910.1	443937.0	60	11	63	-	336	31	20	-	-	11/29/40	-	100	2115	13	1
3501785.7	442223.8	46	40	6	-	305	27	11	-	-	11/29/40	-	85	2190	9	1
3502421.9	437369.3	67	42	6	-	378	39	33	-	-	09/12/40	-	78	2160	13	1
3498167.8	437608.2	100	62	50	-	470	120	70	-	-	09/12/40	-	68	2040	13	1
3497657.0	437312.8	13	57	30	-	116	12	12	-	-	09/11/40	-	45	2020	9	1
3496400.1	439612.4	334	134	480	-	506	698	905	-	-	09/10/40	-	60	2020	14	1
3495148.5	439436.8	85	40	58	-	336	79	93	-	-	02/18/38	-	48	1990	13	1
3494773.9	438500.2	88	44	19	-	384	38	63	-	-	12/05/40	-	60	2015	13	1
3493765.2	436133.6	69	31	1	-	336	-	14	-	-	12/05/40	-	140	2085	1	1
3494250.7	438566.3	87	37	7	-	427	-	18	-	-	12/05/40	-	56	2020	1	1
3494378.1	439347.3	90	53	61	-	372	115	106	-	-	12/05/40	-	50	2010	13	1
3493698.0	439773.3	88	40	14	-	464	12	17	-	-	12/06/40	-	60	2020	1	1
3492204.2	440975.8	94	50	61	-	390	50	138	-	-	12/06/40	-	80	2000	13	1
3492888.4	440871.4	89	54	85	-	458	31	156	-	-	10/01/40	-	100	2010	13	1
3493587.3	442245.6	94	67	93	-	317	123	220	-	-	12/06/40	-	41	1960	16	1
3493456.4	443127.9	244	202	362	-	348	787	770	45.0	-	10/01/40	-	50	1975	16	1
3496653.2	442546.8	91	44	21	-	464	30	29	-	-	04/07/39	-	82	2040	1	1
3496653.2	442546.8	85	44	41	-	488	27	38	-	-	10/01/40	-	82	2040	13	1
3498158.3	443014.5	591	264	998	-	171	2605	1330	-	-	11/29/40	-	109	2080	15	1
3495552.5	445265.8	76	32	17	-	366	20	24	-	-	12/05/40	-	60	1980	1	1
3494444.6	445871.4	68	36	18	-	384	12	21	-	-	12/05/40	-	65	1990	13	1
3493542.2	446760.7	42	36	15	-	287	10	22	-	-	12/05/40	-	65	1985	9	1
3494072.9	446726.8	46	32	49	-	378	12	20	-	-	12/05/40	-	64	1990	13	1
3494295.4	447621.3	88	34	16	-	408	22	26	-	-	12/05/40	-	75	1980	1	1

Appendix 1 (cont). Chemical composition of shallow ground water.

Lat. (utm)	Long. (utm)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	pH	Sample date	Formation*	Sample depth (ft)	Land elevation (ft)	A	B
3494420.7	447904.0	82	40	49	-	433	22	64	-	-	10/01/40	-	85	1990	13	1
3494428.7	447904.1	56	36	25	-	317	15	45	-	-	12/05/40	-	85	1990	13	1
3494980.8	447420.5	67	38	15	-	299	17	62	-	-	12/05/40	-	85	2005	13	1
3497454.4	448887.8	80	90	293	-	525	392	260	-	-	04/05/39	-	200	2180	8	1
3497454.0	448920.0	82	103	487	-	470	461	580	-	-	10/01/40	-	200	2180	8	1
3493792.5	450074.1	89	36	54	-	390	21	96	-	-	10/01/40	-	100	2015	13	1
3491695.7	447309.5	163	55	-	-	323	67	178	36.0	-	02/17/38	-	68	1965	4	1
3490547.1	447962.9	140	89	332	-	421	109	690	-	-	10/01/40	-	71	1945	6	1
3490069.3	450327.6	97	38	19	-	415	24	53	-	-	04/05/39	-	42	1940	1	1
3486707.2	451300.4	191	97	129	-	415	183	420	38.0	-	02/17/38	-	54	1920	14	1
3486715.2	451308.5	128	63	83	-	433	78	220	-	-	09/09/40	-	60	1920	16	1
3486853.5	451840.5	188	82	106	-	366	112	425	22.0	-	09/11/40	-	65	1915	14	1
3486441.9	452679.3	109	51	71	-	433	43	160	-	-	09/11/40	-	75	1910	13	1
3489068.2	454823.4	55	38	95	-	464	51	48	-	-	10/01/40	-	60	1935	13	1
3489365.9	454786.8	279	108	608	-	403	248	1330	-	-	10/01/40	-	60	1940	6	1
3487741.9	458279.0	425	246	1709	-	451	962	3130	-	-	01/12/41	-	70	1900	6	1
3487556.4	459024.0	150	71	282	-	329	78	650	-	-	09/30/40	-	75	1900	14	1
3489323.0	458434.2	174	103	179	-	293	101	630	-	-	04/04/39	-	65	1945	14	1
3489323.3	458410.1	150	91	200	-	293	102	590	-	-	09/30/40	-	77	1945	14	1
3493392.6	459470.4	178	112	136	-	445	543	190	-	-	09/30/40	-	114	2020	16	1
3496106.0	459679.1	60	43	46	-	390	50	36	-	-	09/30/40	-	75	2035	13	1
3499836.8	457417.0	74	28	4	-	323	12	24	-	-	11/29/40	-	119	2300	1	1
3499949.0	453344.5	59	105	3393	-	482	499	4990	-	-	11/28/40	-	90	2120	6	1
3501649.8	454248.4	110	38	2	-	323	29	46	96.0	-	11/28/40	-	66	2180	1	1
3501844.8	455431.8	88	44	166	-	329	383	64	-	-	11/29/40	-	150	2260	15	1
3502326.1	456184.8	70	23	15	-	323	12	16	-	-	11/29/40	-	35	2340	1	1
3503181.9	453784.3	80	24	37	-	354	50	26	-	-	11/28/40	-	50	2205	1	1
3504010.6	469398.1	373	271	105	-	494	1377	310	-	-	09/30/40	-	80	2000	15	1
3502234.4	468750.5	68	48	132	-	256	112	218	-	-	02/18/38	-	110	2040	16	1
3502250.6	468742.6	107	78	83	-	421	101	225	-	-	09/30/40	-	110	2040	16	1
3502265.0	472977.3	75	45	79	-	244	178	106	-	-	10/02/40	-	100	1950	16	1
3497256.8	474675.7	103	60	67	-	348	54	200	29.0	-	10/02/40	-	45	1880	16	1
3497203.1	477030.7	61	36	60	-	305	49	94	-	-	-	-	87	1860	13	1
3495278.5	475708.5	111	61	69	-	226	349	91	-	-	10/02/40	-	50	1855	15	1
3495112.3	474090.7	89	29	50	-	329	45	76	26.0	-	10/02/40	-	90	1860	13	1
3493413.1	472969.7	140	57	136	-	244	543	80	-	-	10/02/40	-	100	1840	15	1
3492387.7	476125.1	212	83	153	-	299	240	480	39.0	-	10/02/40	-	70	1820	14	1
3493498.8	478742.6	283	126	228	-	171	1357	120	-	-	10/02/40	-	85	1800	15	1
3492000.1	479738.2	378	185	237	-	122	1886	110	-	-	01/16/41	-	90	1755	15	1
3491407.1	479578.5	127	68	76	-	336	108	260	-	-	01/16/41	-	60	1770	16	1

Appendix 1 (cont). Chemical composition of shallow ground water.

Lat. (utm)	Long. (utm)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	pH	Sample date	Formation*	Sample depth (ft)	Land elevation (ft)	A	B
3486969.9	487863.5	160	58	57	-	293	83	300	-	-	01/15/41	-	60	1740	2	1
3487414.3	480046.7	126	46	92	-	262	94	270	-	-	01/15/41	-	-	-	14	1
3491338.2	472342.7	431	146	154	-	207	1668	74	-	-	10/02/40	-	50	1810	3	1
3491026.2	471519.1	429	158	173	-	134	1803	76	-	-	10/02/40	-	69	1820	3	1
3489820.9	470090.2	371	121	95	-	268	1060	205	-	-	02/18/38	-	99	1820	3	1
3489796.8	470090.0	458	139	140	-	275	1419	220	-	-	10/02/40	-	99	1820	3	1
3489580.3	470039.2	166	93	141	-	171	408	335	-	-	02/18/38	-	46	1820	16	1
3489580.2	470047.3	190	99	175	-	299	411	370	-	-	10/02/40	-	46	1820	16	1
3488061.6	472063.5	65	38	12	-	348	23	18	-	-	01/22/41	-	50	1780	13	1
3487828.5	469978.7	498	180	60	-	214	1547	230	-	-	01/22/41	-	65	1820	3	1
3487186.5	465027.3	75	38	37	-	329	50	60	21.0	-	02/17/38	-	70	1870	13	1
3487178.4	465035.2	72	39	25	-	360	23	48	-	-	09/30/40	-	70	1870	13	1
3491114.0	464646.8	83	54	44	-	525	53	24	-	-	09/30/40	-	38	1900	13	1
3484291.3	463056.3	490	243	295	-	238	2211	260	-	-	10/02/40	-	175	1870	15	1
3482942.3	460146.6	138	58	41	-	360	26	250	-	-	04/04/39	-	70	1860	2	1
3481668.9	463194.7	61	49	82	-	561	53	13	-	-	10/31/40	-	31	1820	13	1
3482046.7	466663.9	130	68	184	-	390	196	320	31.0	-	10/29/40	-	52	1810	16	1
3483298.4	468953.4	146	114	191	-	403	181	510	-	-	01/22/41	-	45	1780	14	1
3481569.8	469664.9	468	155	435	-	171	1966	400	-	-	10/30/40	-	102	1810	15	1
3480608.6	472137.8	180	73	129	-	282	160	442	-	-	09/08/41	-	85	1825	14	1
3482050.4	471897.3	152	59	106	-	262	138	340	-	-	09/08/41	-	90	1815	14	1
3482781.7	473995.9	341	117	147	-	134	1264	160	-	-	01/25/41	-	125	1820	3	1
3482789.7	473996.0	266	105	146	-	251	686	345	-	-	09/08/41	-	125	1820	15	1
3480845.7	473877.0	102	41	86	-	282	88	200	-	-	09/08/41	-	86	1825	16	1
3479451.4	472100.3	87	41	97	-	220	92	220	-	-	10/31/40	-	65	1830	14	1
3478963.1	472617.2	120	40	92	-	293	88	230	-	-	11/19/40	-	90	1830	16	1
3477384.4	477073.6	87	45	16	-	256	69	106	-	-	11/18/40	-	55	1800	16	1
3476491.6	479871.3	102	20	103	-	348	104	110	-	-	11/01/40	-	80	1790	13	1
3478796.8	479559.5	127	49	52	-	311	142	154	-	-	10/29/40	-	60	1780	4	1
3482477.7	475985.3	185	89	106	-	250	576	180	-	-	10/29/40	-	-	-	15	1
3481966.6	478764.3	129	41	72	-	268	123	200	-	-	10/29/40	-	75	1805	16	1
3481871.1	484849.0	584	269	230	-	232	2630	94	-	-	10/29/40	-	80	1755	15	1
3483715.5	485426.1	177	69	64	-	293	106	355	21.0	-	01/15/41	-	58	1760	2	1
3484781.9	484751.1	146	63	83	-	232	72	380	-	-	01/15/41	-	70	1755	14	1
3485577.9	488578.6	157	52	81	-	299	121	270	38.0	-	01/15/41	-	60	1750	2	1
3480127.3	486829.1	130	63	123	-	281	200	260	55.0	-	10/29/40	-	38	1755	16	1
3478928.0	488057.8	130	46	179	-	275	211	290	60.0	-	10/29/40	-	38	1760	16	1
3476762.5	486384.9	118	53	62	-	354	125	150	-	-	10/31/40	-	48	1770	16	1
3478547.6	484252.4	236	132	156	-	323	282	630	27.0	-	10/29/40	-	50	1770	14	1
3473918.9	482994.5	488	157	368	-	275	2138	148	-	-	10/31/40	-	90	1810	15	1

Appendix 1 (cont). Chemical composition of shallow ground water.

Lat. (utm)	Long. (utm)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	pH	Sample date	Formation*	Sample depth (ft)	Land elevation (ft)	A	B
3473346.5	482831.5	83	58	90	-	378	197	90	-	-	10/31/40	-	60	1815	16	1
3473134.4	483588.0	132	90	147	-	293	614	98	-	-	11/11/40	-	70	1800	15	1
3473456.2	486204.9	171	75	98	-	329	217	310	-	-	10/31/40	-	50	1805	16	1
3469505.5	488169.4	144	69	94	-	262	238	265	-	-	11/15/40	-	60	1845	16	1
3469679.5	487511.6	102	53	27	-	317	169	68	-	-	11/15/40	-	60	1845	16	1
3469010.7	486670.3	100	38	6	-	79	315	20	-	-	11/15/40	-	68	1845	3	1
3470068.6	483993.6	123	59	72	-	409	169	140	-	-	11/11/40	-	85	1830	16	1
3470908.0	477070.7	70	55	50	-	329	24	154	-	-	02/15/38	-	125	1860	13	1
3470922.6	476829.6	59	66	56	-	226	79	195	-	-	02/15/38	-	125	1860	10	1
3472352.0	475470.9	308	123	158	-	201	1098	220	-	-	11/06/40	-	92	1850	15	1
3473864.2	477035.9	252	76	132	-	275	753	155	-	-	11/01/40	-	90	1830	3	1
3476031.3	475455.7	148	53	113	-	262	154	320	-	-	11/01/40	-	70	1820	14	1
3475505.4	472299.1	110	46	109	-	238	100	280	-	-	11/01/40	-	70	1830	14	1
3472850.8	473041.6	93	35	86	-	281	104	160	-	-	11/06/40	-	90	1855	16	1
3471105.5	471597.6	115	51	110	-	275	225	185	-	-	02/15/38	-	123	1870	16	1
3475740.9	468884.4	143	57	108	-	214	138	333	46.0	-	11/01/40	-	85	1835	14	1
3471508.6	465250.0	121	49	113	-	281	133	260	-	-	02/15/38	-	100	1860	16	1
3471532.9	465226.1	111	44	140	-	293	86	300	-	-	10/03/40	-	100	1860	14	1
3471723.8	465047.2	121	48	107	-	280	133	255	-	-	02/15/38	-	130	1860	16	1
3475759.2	465447.4	163	66	239	-	256	127	600	-	-	11/01/40	-	88	1855	14	1
3474780.1	463067.6	277	135	99	-	226	132	1100	-	-	10/22/40	-	75	1865	14	1
3473695.0	462978.1	128	52	149	-	317	97	345	-	-	10/22/40	-	60	1865	14	1
3475947.5	461964.5	680	117	308	-	226	2059	368	-	-	02/15/38	-	116	1870	3	1
3475963.5	461972.6	536	167	265	-	244	1881	314	-	-	10/03/40	-	116	1870	3	1
3478237.1	460924.9	563	184	366	-	290	2100	375	-	-	08/19/40	-	110	1840	15	1
3476251.5	460712.5	112	60	62	-	317	183	132	26.0	-	02/15/38	-	100	1870	16	1
3476267.5	460712.4	107	54	66	-	317	171	122	28.0	-	10/03/40	-	100	1870	16	1
3476204.0	459996.9	112	57	66	-	378	89	146	60.0	-	09/04/40	-	67	1865	13	1
3475400.4	454443.6	61	18	35	-	311	12	21	-	-	08/21/40	-	43	1900	1	1
3478423.1	453484.5	39	10	75	-	140	20	114	-	-	08/22/40	-	-	-	6	1
3478688.2	452221.6	2880	880	37526	-	427	4160	62200	-	-	08/22/40	-	714	2074	6	1
3478879.9	452035.6	59	50	18	-	415	23	17	-	-	08/26/40	-	20	1910	9	1
3477751.7	444976.2	100	72	284	-	506	249	330	22.0	-	08/26/40	-	60	2080	8	1
3474211.0	447505.1	145	28	41	-	537	58	44	-	-	02/18/38	-	46	1970	1	1
3474202.9	447505.0	227	41	80	-	421	478	42	-	-	08/22/40	-	46	1970	3	1
3473385.1	444130.4	66	52	163	-	421	66	220	-	-	08/22/40	-	110	1980	16	1
3474212.0	443878.7	65	51	115	-	378	33	192	-	-	08/26/40	-	120	2000	13	1
3474439.0	441835.9	67	42	51	-	415	27	56	-	-	08/26/40	-	60	1985	13	1
3474526.9	440337.1	107	59	96	-	470	27	210	-	-	08/26/40	-	60	1970	13	1
3476833.6	442474.2	94	54	86	-	323	29	230	30.0	-	08/26/40	-	80	2020	14	1

Appendix 1 (cont). Chemical composition of shallow ground water.

Lat. (utm)	Long. (utm)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	pH	Sample date	Formation*	Sample depth (ft)	Land elevation (ft)	A	B
3477922.5	442613.1	62	39	25	-	354	10	28	33.0	-	08/26/40	-	83	2045	13	1
3478581.9	442675.4	126	122	282	-	482	148	620	-	-	08/26/40	-	40	2040	14	1
3478971.6	444628.6	134	91	270	-	244	230	570	66.0	-	08/26/40	-	120	2100	14	1
3479821.3	443231.7	137	88	243	-	281	233	530	-	-	09/03/40	-	60	2080	14	1
3479851.2	441840.9	16	47	107	-	494	18	26	-	-	09/03/40	-	40	2070	13	1
3479472.6	441731.2	150	180	776	-	451	206	1570	-	-	09/03/40	-	151	2065	6	1
3478642.1	439213.4	138	122	230	-	366	214	580	-	-	08/26/40	-	87	2120	14	1
3475290.7	436430.7	40	46	116	-	494	67	40	-	-	08/27/40	-	60	2000	13	1
3471623.1	435720.6	63	24	31	-	342	13	20	-	-	08/27/40	-	150	2220	13	1
3470535.6	437569.7	256	128	1187	-	378	544	2030	-	-	08/27/40	-	125	2080	6	1
3470800.3	439665.4	108	37	158	-	384	56	271	-	-	08/27/40	-	74	2000	14	1
3471878.9	442044.7	52	43	100	-	397	113	47	-	-	08/22/40	-	25	1940	13	1
3470418.5	442377.0	72	46	160	-	384	144	176	-	-	08/23/40	-	46	1940	16	1
3470829.2	441393.4	65	42	161	-	580	105	64	-	-	08/22/40	-	30	1950	5	1
3469898.7	440572.3	79	49	127	-	500	28	166	-	-	08/22/40	-	80	1980	13	1
3468776.7	438860.5	66	70	621	-	403	478	678	20.0	-	02/21/38	-	45	2010	6	1
3466390.2	438845.7	70	31	110	-	421	93	70	-	-	08/23/40	-	35	1980	13	1
3464138.9	438748.0	101	52	255	-	445	288	240	20.0	-	08/23/40	-	50	2020	8	1
3457095.8	436479.4	69	41	58	-	427	58	32	-	-	08/27/40	-	35	2070	13	1
3457866.4	439592.4	91	27	36	-	415	22	32	-	-	08/21/40	-	80	2070	1	1
3459447.8	440392.6	116	24	15	-	409	26	37	-	-	08/21/40	-	65	2040	1	1
3459473.5	439516.2	74	24	35	-	354	28	28	-	-	08/27/40	-	-	-	1	1
3460278.3	439646.9	64	26	52	-	305	62	42	-	-	08/27/40	-	67	2040	13	1
3460441.2	438936.2	71	22	91	-	427	58	38	-	-	08/27/40	-	50	2050	13	1
3461749.3	438566.9	76	31	55	-	323	50	64	38.0	-	08/27/40	-	60	2040	13	1
3461991.9	440936.4	137	59	193	-	360	229	320	23.0	-	08/21/40	-	47	2000	16	1
3464534.5	441930.5	52	30	44	-	323	31	36	-	-	08/23/40	-	40	1970	13	1
3466921.4	441657.9	77	42	116	-	409	140	92	-	-	08/23/40	-	85	1970	13	1
3468968.9	443428.4	162	69	324	-	378	272	560	-	-	08/23/40	-	65	1950	6	1
3468402.3	444796.9	123	49	288	-	409	295	345	-	-	08/23/40	-	40	1950	8	1
3465589.9	444251.1	69	32	67	-	366	70	53	-	-	08/21/40	-	30	1970	13	1
3463689.1	443799.3	74	57	22	-	275	-	20	-	-	08/21/40	-	87	2020	9	1
3464572.4	448929.8	203	59	194	-	317	47	600	24.0	-	09/04/40	-	90	1970	14	1
3464603.3	450875.1	140	37	72	-	458	43	170	-	-	09/04/40	-	65	1960	1	1
3464517.6	452290.7	130	37	92	-	348	51	230	29.0	-	09/04/40	-	80	1945	16	1
3469425.9	448627.5	116	52	188	-	403	187	270	-	-	08/23/40	-	25	1910	16	1
3470762.5	453119.4	137	48	226	-	342	334	280	-	-	08/21/40	-	30	1890	16	1
3473125.4	459213.5	15	58	20	-	49	12	44	-	-	09/04/40	-	40	1885	10	1
3470230.7	459069.6	190	74	208	-	256	70	670	-	-	09/04/40	-	80	1910	14	1
3469421.2	458556.2	187	68	249	-	329	121	630	-	-	09/04/40	-	90	1910	14	1

Appendix 1 (cont). Chemical composition of shallow ground water.

Lat. (utm)	Long. (utm)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	pH	Sample date	Formation*	Sample depth (ft)	Land elevation (ft)	A	B
3464841.5	465239.7	111	49	105	-	348	93	230	-	-	10/06/40	-	129	1905	16	1
3462456.2	464502.2	79	34	57	-	305	62	102	-	-	10/17/40	-	160	1935	13	1
3461023.6	467455.5	92	24	9	-	293	66	30	-	-	10/15/40	-	150	1980	1	1
3462280.3	468852.9	427	198	3420	-	244	1734	5190	-	-	05/12/37	-	260	1980	6	1
3462919.5	467272.3	104	27	54	-	378	47	90	-	-	10/15/40	-	126	1935	1	1
3464916.8	467053.1	67	42	796	-	372	621	790	-	-	10/15/40	-	130	1905	6	1
3465782.0	468690.5	527	198	1826	-	311	1416	3100	-	-	10/17/40	-	105	1895	6	1
3464955.9	469336.2	771	292	3990	-	500	2814	6000	-	-	10/17/40	-	112	1920	6	1
3466543.9	471312.6	284	63	188	-	305	714	270	-	-	10/22/40	-	100	1920	3	1
3467686.0	470331.1	269	95	573	-	299	520	1080	-	-	10/22/40	-	107	1890	6	1
3467285.1	468356.4	92	30	83	-	305	87	134	-	-	10/17/40	-	107	1880	16	1
3469183.2	466348.2	127	51	150	-	287	105	360	-	-	10/17/40	-	90	1865	14	1
3469175.0	469491.7	106	30	104	-	305	101	180	-	-	10/22/40	-	90	1865	16	1
3468873.1	472074.6	179	65	161	-	268	295	380	-	-	10/22/40	-	100	1885	14	1
3470551.0	473648.5	134	46	102	-	317	140	240	-	-	10/22/40	-	102	1870	16	1
3470606.3	473954.0	271	97	215	-	305	791	330	-	-	10/22/40	-	127	1870	15	1
3469292.5	475307.3	81	51	45	-	207	96	170	-	-	11/14/40	-	101	1880	16	1
3468521.4	475353.8	111	51	55	-	336	192	93	-	-	11/14/40	-	96	1890	16	1
3465764.6	475747.4	131	65	58	-	299	369	64	-	-	11/14/40	-	110	1920	15	1
3466412.2	476817.8	104	37	6	-	342	76	60	-	-	11/14/40	-	108	1915	1	1
3467223.0	483242.3	140	77	61	-	329	312	141	-	-	02/15/38	-	74	1865	16	1
3467191.1	484551.5	136	110	142	-	122	312	480	-	-	11/15/40	-	80	1870	14	1
3467111.1	489097.3	360	179	90	-	293	1172	240	41.0	-	02/15/38	-	100	1860	15	1
3467099.1	489136.0	380	209	254	-	256	1745	220	29.0	-	10/03/40	-	100	1860	15	1
3465714.6	485918.9	373	220	123	-	317	1536	170	-	-	11/15/40	-	102	1880	15	1
3465321.0	485907.7	253	57	36	-	384	575	21	-	-	11/15/40	-	90	1890	3	1
3458346.5	475836.7	78	22	22	-	293	50	28	-	-	10/30/40	-	15	2000	1	1
3457482.3	475429.9	80	20	13	-	293	31	28	-	-	10/15/40	-	-	-	1	1
3455138.5	485199.1	84	29	23	-	378	24	27	-	-	10/18/40	-	55	2050	1	1
3447299.9	487657.2	76	22	23	-	299	-	21	-	-	10/18/40	-	-	-	1	1
3447726.5	485805.1	62	29	23	-	299	43	21	-	-	10/18/40	-	173	2160	13	1
3450555.9	465350.3	64	16	23	-	275	-	29	-	-	10/10/40	-	110	2180	1	1
3454668.4	462498.9	75	18	24	-	299	25	24	-	-	02/16/38	-	-	-	1	1
3454644.3	462498.8	78	17	32	-	329	14	31	-	-	10/10/40	-	-	-	1	1
3463792.6	457857.9	112	31	54	-	311	83	129	-	-	02/16/38	-	25	1950	4	1
3463815.9	457830.3	60	20	32	-	293	27	24	-	-	09/04/40	-	25	1950	13	1
3455707.4	453434.4	108	23	7	-	342	25	44	-	-	02/16/38	-	52	2015	1	1
3455715.6	453442.3	99	18	22	-	372	18	30	-	-	10/21/40	-	52	2015	1	1
3450519.9	452760.1	71	45	1638	-	952	707	1705	-	-	02/17/38	-	367	2040	6	1
3450241.8	451503.4	60	100	2902	-	445	832	4000	-	-	02/16/38	-	700	2060	6	1

Appendix 1 (cont). Chemical composition of shallow ground water.

Lat. (utm)	Long. (utm)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	pH	Sample date	Formation*	Sample depth (ft)	Land elevation (ft)	A	B
3450249.9	451495.4	229	101	3778	-	878	892	5350	-	-	10/03/40	-	700	2060	6	1
3448891.4	451740.4	117	105	38	-	329	449	28	36.0	-	02/18/38	-	50	2050	11	1
3444855.1	452837.3	60	17	31	-	287	-	27	-	-	08/20/40	-	-	-	1	1
3447487.5	458161.6	80	14	12	-	293	10	21	-	-	10/21/40	-	140	2175	1	1
3441091.2	450973.6	69	16	15	-	275	17	15	-	-	02/17/38	-	120	2115	1	1
3441099.2	450981.7	38	16	24	-	195	-	30	-	-	10/03/40	-	120	2115	13	1
3441890.6	447158.2	81	12	19	-	305	16	19	-	-	10/14/40	-	120	2170	1	1
3442660.5	443030.2	94	22	81	-	299	93	110	-	-	10/14/40	-	220	2280	16	1
3499152.8	449025.4	60	73	211	-	354	377	159	1.5	7.9	07/20/50	KCT	200	2180	8	2
3503770.0	466110.0	86	67	43	-	360	74	140	18.0	7.4	03/21/50	KCT	175	2080	13	2
3503481.1	456001.7	201	81	96	-	180	780	55	7.2	-	01/28/49	KCT-QLe	158	2240	15	2
3506050.3	474676.2	65	48	13	-	284	37	75	12.0	-	10/07/48	PLC	132	1985	9	2
3504144.4	474731.8	73	45	25	-	294	32	78	45.0	-	10/07/48	PLC	140	1965	13	2
3503806.4	474777.0	34	39	20	-	184	31	67	16.0	-	10/07/48	PLC	82	1947	9	2
3503666.5	473312.6	76	41	46	-	370	45	50	45.0	-	01/28/49	PLC	120	1970	13	2
3502706.4	474614.6	63	40	26	-	322	36	40	25.0	-	10/07/48	PLC	79	1928	13	2
3502213.5	475808.2	84	30	37	-	322	32	50	56.0	-	10/07/48	PLC	79	1922	1	2
3501045.3	423794.8	75	54	23	-	371	55	63	6.1	8.0	07/21/50	KCT	116	2190	13	2
3498064.9	426249.1	68	36	7	-	363	9	11	6.6	8.2	07/20/50	KCT	65	2310	1	2
3496830.0	423631.8	50	47	19	-	334	20	26	26.0	8.1	07/20/50	KCT	72	2310	9	2
3496295.7	419393.5	62	24	17	-	277	39	12	6.1	7.8	07/25/50	KCT	125	2280	1	2
3495972.7	422097.5	150	63	26	-	277	421	17	0.5	8.1	07/21/50	KCT	209	2305	3	2
3502666.4	428963.0	60	45	18	-	362	24	36	0.0	8.1	07/20/50	KCT	160	2100	13	2
3497366.0	430396.8	384	231	140	-	191	1770	151	0.0	7.7	07/06/50	-	178	2230	15	2
3496889.5	429432.0	64	31	15	-	302	34	13	3.2	7.9	07/28/50	KCT	120	2220	13	2
3501975.4	448539.8	82	52	215	-	331	329	192	1.2	7.8	07/20/50	KCT	150	2220	8	2
3499949.3	459715.3	56	53	101	-	424	144	56	0.5	7.3	05/02/50	KCT	77	2100	13	2
3501581.5	474797.2	88	51	71	-	380	60	130	33.0	-	10/07/48	PLC	83	1918	13	2
3499404.0	474834.9	76	41	37	-	358	31	71	16.0	-	10/07/48	PLC	89	1890	13	2
3500129.9	475381.4	58	38	13	-	320	19	28	8.0	-	10/07/48	PLC	116	1900	13	2
3498829.1	473128.4	62	49	30	-	326	38	76	9.5	-	01/24/49	PLC	100	1920	13	2
3497946.1	474805.3	87	40	63	-	436	56	71	2.2	-	10/07/48	PLC	104	1885	13	2
3497335.4	475067.8	77	46	37	-	368	37	81	9.0	-	10/07/48	PLC	57	1875	13	2
3495825.5	475566.0	98	60	52	-	272	242	85	12.0	-	10/07/48	PLC	45	1850	16	2
3490950.1	421625.5	41	36	25	-	242	81	16	0.0	8.2	07/27/50	KCT	148	2400	13	2
3490116.1	408524.0	48	29	12	-	256	23	18	7.2	8.3	07/25/50	KCT	135	2420	13	2
3489403.8	415147.8	76	26	9	-	347	12	12	4.8	8.1	07/27/50	KCT	72	2310	1	2
3492724.8	430586.2	84	29	10	-	382	16	12	5.0	7.8	07/07/50	KCT-QLe	48	2180	1	2
3485113.1	438643.5	68	38	19	-	392	19	13	0.2	8.0	07/11/50	KCT	205	2300	13	2
3476234.1	437073.3	24	54	59	-	346	46	51	3.5	8.2	09/15/50	QLe	51	2000	9	2

Appendix 1 (cont). Chemical composition of shallow ground water.

Lat. (utm)	Long. (utm)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	pH	Sample date	Formation*	Sample depth (ft)	Land elevation (ft)	A	B
3491161.9	450508.0	88	39	37	-	400	28	66	8.5	7.8	06/15/50	QLe	90	1964	13	2
3488739.8	458122.7	156	118	265	-	285	137	750	20.0	7.1	05/05/50	PGPR	99	1925	14	2
3475879.1	459759.5	904	340	431	-	308	1470	1990	3.5	-	10/11/48	PLC	135	1860	14	2
3476644.2	459720.6	93	57	80	-	364	98	152	32.0	-	10/11/48	PLC	63	1859	16	2
3476739.7	450788.1	32	158	195	-	482	472	160	45.0	8.2	09/14/50	PGPR	29	1960	12	2
3493677.1	461537.3	54	41	29	-	370	29	17	12.0	7.5	05/03/50	PGPR	60	1980	13	2
3489409.8	465187.8	50	52	40	-	375	52	27	34.0	7.5	03/21/50	QLe	40	1880	9	2
3493308.8	472921.8	52	35	39	-	300	20	65	1.2	-	01/28/49	PLC	85	1840	13	2
3493304.2	475681.6	614	108	73	-	188	1680	152	22.0	-	10/07/48	PLC	98	1831	3	2
3488194.3	475839.1	212	113	106	-	250	662	232	2.2	-	09/24/48	PLC	42	1731	15	2
3482091.8	475727.1	386	164	160	-	158	1340	325	3.8	-	09/27/48	PLC	120	1816	15	2
3481476.2	472373.7	108	52	107	-	277	129	245	12.0	-	10/27/48	QLe	110	1822	16	2
3481446.7	471879.7	234	103	126	-	240	281	545	30.0	-	11/03/48	PLC-QLe	150	1820	14	2
3480992.0	470565.8	138	52	90	-	240	111	288	46.0	-	10/26/48	PLC-QLe	114	1820	14	2
3481100.4	469783.5	146	59	49	-	256	112	252	39.0	-	10/26/48	PLC-QLe	177	1818	2	2
3478467.8	461107.0	194	110	186	-	314	263	560	24.0	-	10/12/48	PLC	73	1840	14	2
3478480.2	462649.6	228	158	121	-	90	217	830	13.0	-	10/16/48	PLC	80	1840	14	2
3478875.5	467060.5	96	34	35	-	256	34	134	26.0	-	01/20/49	QLe	70	1836	4	2
3479363.5	472538.1	106	44	106	-	258	86	255	18.0	-	01/20/49	QLe	96	1829	14	2
3479443.6	474447.2	84	46	90	-	196	86	230	24.0	-	10/27/48	PLC-QLe	100	1825	14	2
3479357.0	474848.7	448	193	147	-	198	1730	190	0.0	-	11/03/48	PLC-QLe	119	1822	3	2
3478872.8	476035.6	100	45	71	-	260	81	198	15.0	-	11/03/48	QLe	100	1811	16	2
3476832.4	463013.1	308	138	210	-	64	912	560	2.5	-	10/12/48	PLC	80	1860	15	2
3491339.9	479885.7	254	101	189	-	237	1060	126	1.8	8.0	04/19/51	PLC	180	1750	15	2
3491107.1	479027.4	454	162	246	-	258	1760	185	-	7.8	08/01/50	PLC	218	1785	15	2
3487068.7	479592.2	130	54	96	-	265	216	201	23.0	7.3	01/04/51	PLC-QLe	153	1770	16	2
3483255.7	478635.5	108	42	88	-	265	102	220	19.0	7.5	04/19/51	QLe	101	1805	16	2
3483091.5	478779.4	112	43	86	-	267	114	204	24.0	7.2	01/30/51	PLC	155	1803	16	2
3481722.5	488132.9	148	75	74	-	424	153	205	53.0	-	09/27/48	PLC	67	1736	16	2
3480194.8	486929.6	114	35	101	-	232	150	175	68.0	-	01/20/49	PLC	25	1750	16	2
3478597.3	484623.3	199	73	192	-	288	297	400	129.0	-	01/20/49	PLC	67	1770	14	2
3478925.9	483122.1	408	192	205	-	100	1930	185	0.0	-	01/20/49	PLC	103	1760	15	2
3475035.6	442542.5	66	40	46	-	348	20	84	4.5	7.5	09/14/50	QLe	73	2000	13	2
3472229.9	452815.3	2460	1050	16000	-	405	3180	29500	-	-	10/08/48	PGPR	122	1900	6	2
3467897.6	445075.1	123	49	288	-	409	295	345	-	-	08/23/49	QLe	37	1950	8	2
3474549.9	462613.1	382	189	457	-	242	246	1600	15.0	-	11/12/48	PLC	100	1865	14	2
3474833.5	462820.2	390	179	541	-	244	178	1760	23.0	-	11/12/48	PLC-QLe	87	1863	14	2
3474102.0	474838.4	121	53	93	-	282	116	258	8.7	-	09/27/48	QLe	78	1835	14	2
3473430.1	461731.8	454	193	700	-	254	425	1970	24.0	-	04/09/48	PLC-QLe	100	1875	14	2
3471611.9	462814.6	174	65	195	-	332	100	530	30.0	7.3	08/28/50	PLC-QLe	92	1880	14	2

Appendix 1 (cont). Chemical composition of shallow ground water.

Lat. (utm)	Long. (utm)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	pH	Sample date	Formation*	Sample depth (ft)	Land elevation (ft)	A	B
3472934.8	471955.0	103	44	90	-	275	93	215	9.0	-	12/16/48	QLe	110	1855	16	2
3471122.8	474176.8	247	72	98	-	299	464	267	2.5	7.7	08/30/50	PLC-QLe	140	1863	4	2
3471034.5	469955.1	108	44	120	-	290	96	253	9.0	7.5	08/28/50	QLe	117	1861	14	2
3470637.2	475499.4	112	47	58	-	326	203	85	0.0	-	09/22/48	PLC	95	1867	16	2
3469556.2	475274.8	179	69	45	-	275	440	100	3.5	-	12/23/48	PLC	207	1880	3	2
3467385.3	469864.4	124	41	136	-	292	134	276	6.3	7.5	08/28/50	QLe	128	1888	14	2
3472752.7	488081.7	544	228	124	-	244	2140	98	0.0	-	12/08/48	PLC	62	1820	3	2
3467205.4	487222.1	530	243	151	-	242	2200	115	0.0	-	01/27/49	PLC	78	1865	15	2
3465255.5	483258.8	112	82	84	-	318	263	188	0.0	-	01/20/49	PLC	98	1895	16	2
3455961.9	435829.1	66	34	289	-	308	307	252	2.0	7.9	09/21/50	KCT	60	2080	8	2
3453325.4	445117.5	52	33	613	-	343	528	540	6.9	7.4	05/19/50	KCT	148	2150	8	2
3452502.6	452362.3	90	26	71	-	378	75	62	14.0	7.9	05/18/50	KCT	60	2010	13	2
3449322.7	448349.0	78	21	10	-	310	14	16	13.0	7.8	05/18/50	KCF	57	2200	1	2
3496396.2	437764.0	82	52	43	-	378	104	64	4.0	8.0	07/07/50	QLe	66	2015	13	2
3496396.3	437788.2	90	52	42	-	390	100	68	3.8	7.2	08/19/47	QLe	66	2015	13	2
3483980.4	472494.5	220	97	117	-	287	181	525	47.0	-	04/06/48	PLC-QLe	79	1805	14	2
3482029.6	477758.7	98	46	84	-	274	112	184	19.0	-	11/05/48	QLe	103	1810	16	2
3468880.8	474855.7	302	118	66	-	240	914	165	1.2	-	01/03/49	PLC	214	1884	3	2
3450107.1	442854.3	67	25	14	-	308	16	19	4.8	8.0	05/19/50	KCT	177	2255	1	2
3487778.0	417930.7	80	33	18	-	411	13	11	-	7.7	09/13/67	QAl-KCT	80	2300	1	3
3485399.4	419996.4	72	32	19	-	361	23	20	-	7.8	09/11/67	QAl	45	2220	1	3
3485499.1	430392.2	51	36	33	-	333	36	22	-	7.7	10/03/67	KCT	165	2240	13	3
3481309.0	417293.1	53	33	11	-	296	28	11	-	7.9	09/12/67	KCF-KCT	120	2330	13	3
3480689.8	420921.1	66	31	7	-	316	12	12	-	7.7	09/12/67	KCT	91	2260	1	3
3484047.9	421496.4	72	32	16	-	361	21	16	-	7.7	09/11/67	QAl	39	2190	1	3
3482339.7	428236.0	97	58	31	-	439	15	63	-	-	05/15/40	KCT	90	2120	13	3
3482299.9	428235.4	138	56	54	-	432	77	136	-	7.5	10/05/67	KCT	75	2120	13	3
3477416.0	416829.2	72	41	31	-	412	36	26	-	7.8	08/09/68	QAl-KCT	55	2180	13	3
3476616.1	420303.3	500	173	70	-	184	1780	66	-	7.4	09/15/67	QAl-KCT	121	2130	3	3
3478406.0	425168.9	145	108	129	-	421	208	351	-	7.6	09/08/67	QAl-KCT	52	2090	16	3
3471600.1	418827.7	85	30	8	-	395	10	7	-	7.4	07/12/67	KCT	52	2200	1	3
3475296.9	418302.5	37	49	61	-	342	68	55	-	-	05/21/40	KCT-TrD	40	2130	13	3
3475296.8	418310.4	208	126	210	-	378	713	310	-	-	06/25/40	KCT-TrD	95	2130	16	3
3475312.9	418294.7	81	53	42	-	436	64	60	-	7.8	07/22/68	KCT-TrD	56	2130	13	3
3472814.0	421999.9	84	42	16	-	444	14	25	-	7.3	07/12/67	KCT	73	2180	1	3
3474404.0	427556.8	79	37	14	-	405	17	18	-	7.9	10/06/67	KCT	100	2180	1	3
3474603.6	425362.3	58	40	41	-	375	65	22	-	7.8	10/06/67	KCT	143	2200	13	3
3484160.9	433242.1	49	34	40	-	295	72	24	-	7.9	10/03/67	KCT	115	2140	13	3
3478960.8	429001.4	125	59	61	-	403	18	240	-	-	06/25/40	QAl-P	65	2080	16	3
3478968.4	429025.4	141	75	75	-	317	70	324	-	7.6	10/05/67	QAl-P	90	2080	14	3

Appendix 1 (cont). Chemical composition of shallow ground water.

Lat. (utm)	Long. (utm)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	pH	Sample date	Formation*	Sample depth (ft)	Land elevation (ft)	A	B
3477051.6	429427.1	114	49	177	-	361	115	320	-	7.5	10/25/66	QAl-P	40	2040	14	3
3478303.3	430934.4	85	50	25	-	378	16	100	-	-	06/25/40	QAl-P	72	2085	13	3
3479876.0	430105.7	119	91	174	-	405	97	432	-	7.6	10/05/67	QAl-P	108	2100	14	3
3478244.9	433274.3	64	27	32	-	332	26	32	-	7.5	09/07/67	QAl	65	2020	13	3
3467161.7	418182.5	59	22	15	-	276	15	16	-	7.8	07/22/68	KCT	240	2430	1	3
3470142.5	417971.6	77	21	19	-	292	29	31	-	7.4	07/22/68	KCF	236	2350	1	3
3470122.1	419611.9	59	26	9	-	281	18	16	-	7.3	07/22/68	KCT-TrD	270	2360	1	3
3469528.4	421998.8	69	20	9	-	293	12	13	-	7.5	08/07/67	KCT	70	2210	1	3
3468291.4	424813.7	310	154	276	-	265	1240	346	-	7.5	08/07/67	P	113	2180	15	3
3462692.2	416680.5	70	23	29	-	272	29	49	-	7.4	02/28/68	KCF-KCT	73	2330	1	3
3464134.4	417633.9	58	27	13	-	284	24	15	-	7.8	02/28/68	KCT	150	2340	1	3
3462444.7	419335.4	58	30	5	-	304	11	9	-	7.7	02/28/68	KCF-KCT	185	2350	1	3
3462157.8	424051.4	129	52	80	-	357	141	181	-	7.5	08/29/67	QAl	44	2150	16	3
3465551.3	424931.1	610	201	665	-	253	2298	851	-	-	09/26/60	P	202	2160	15	3
3465543.4	424931.0	640	190	690	-	234	2270	880	-	7.2	08/07/67	P	202	2160	15	3
3464457.9	424596.0	95	29	35	-	354	57	56	-	7.2	08/07/67	QAl-KCT	65	2140	1	3
3465388.1	428319.6	96	40	112	-	320	213	128	-	7.9	07/19/68	QAl-P	70	2090	16	3
3465800.2	427920.0	202	75	234	-	453	449	342	-	7.5	12/08/67	QAl-P	40	2090	16	3
3463696.5	427020.2	171	83	331	-	327	700	359	-	7.5	07/19/68	QAl-KCT	89	2140	16	3
3465334.6	427719.2	139	51	122	-	428	157	233	-	7.9	07/23/68	QAl-P	52	2090	16	3
3459526.8	419849.1	69	29	9	-	268	31	42	-	-	07/23/40	KCF-KCT	150	2355	1	3
3459534.6	419857.2	75	33	14	-	388	4	19	-	7.3	10/25/66	KCF-KCT	150	2355	1	3
3457933.3	416857.0	48	33	32	-	287	29	41	-	-	06/06/40	KCT	200	2400	13	3
3457925.5	416848.9	54	29	30	-	276	35	39	-	7.8	07/24/68	KCT	220	2400	13	3
3458279.4	419734.6	96	53	201	-	323	292	230	-	-	07/23/40	KCF-KCT	190	2315	16	3
3458287.2	419742.7	72	29	47	-	299	67	63	-	7.6	07/25/68	KCF-KCT	190	2315	13	3
3459496.4	421845.8	89	30	8.5	-	334	40	28	-	-	09/25/41	KCF-KCT	62	2210	1	3
3459504.4	421837.9	111	33	35	-	415	52	58	-	7.4	08/08/68	KCF-KCT	80	2210	1	3
3458255.1	421325.6	100	54	179	-	330	307	182	-	7.8	08/20/47	KCT	150	2280	16	3
3458262.9	421333.6	97	49	175	-	276	340	189	-	7.2	07/18/68	KCT	180	2280	16	3
3459170.3	422358.0	125	53	137	-	510	178	163	-	7.5	08/08/68	QAL-KCT	87	2185	13	3
3459211.6	421212.8	140	67	193	-	354	449	219	-	7.4	07/18/68	KCF-KCT	185	2230	16	3
3458693.9	421769.9	70	40	123	-	388	155	100	-	7.5	10/03/66	KCT	150	2250	13	3
3458271.6	422328.4	98	21	52	-	315	79	66	-	7.4	08/16/67	QAl-P	204	2180	1	3
3460951.7	423871.7	157	82	230	-	328	560	281	-	8.0	08/15/67	KCT-TrD	120	2200	16	3
3458937.9	421255.3	97	52	220	-	329	300	250	-	-	06/21/40	KCT	165	2240	8	3
3459009.5	422314.7	115	50	115	-	490	141	138	-	7.4	08/08/68	QAl-KCT	54	2185	13	3
3458753.4	425072.1	91	54	239	-	332	331	237	-	7.7	12/20/67	KCF-KCT	128	2250	8	3
3463925.0	432024.9	510	310	1530	-	115	1760	2900	-	7.3	07/19/68	P	87	2240	6	3
3463997.7	429829.7	77	36	142	-	328	162	160	-	7.6	07/19/68	QAl-P	139	2140	16	3

Appendix 1 (cont). Chemical composition of shallow ground water.

Lat. (utm)	Long. (utm)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	pH	Sample date	Formation*	Sample depth (ft)	Land elevation (ft)	A	B
3465885.0	431863.2	127	68	350	-	332	384	510	-	7.7	07/19/68	QAl-P	100	2050	6	3
3457991.0	429747.7	74	38	125	-	281	19	262	-	7.5	12/19/67	KCF-KCT	266	2400	14	3
3461040.8	429077.2	78	43	342	-	362	338	327	-	7.8	12/19/67	KCT	135	2200	8	3
3453437.8	416573.5	72	20	21	-	276	21	33	-	7.2	08/14/68	KCF-KCT	147	2320	1	3
3453096.4	418645.3	76	18	28	-	281	43	37	-	-	07/05/40	KCF	74	2290	1	3
3453096.2	418661.2	105	21	131	-	316	51	227	-	7.3	08/14/68	KCF	74	2290	14	3
3455908.1	421604.1	90	17	9	-	281	41	27	-	-	05/24/40	KCF	12	2220	1	3
3455908.1	421604.1	89	18	21	-	307	30	38	-	7.3	08/17/67	KCF	11	2220	1	3
3457257.8	420707.2	96	45	141	-	342	199	170	-	-	07/23/40	KCT	110	2240	16	3
3456738.5	421997.6	78	53	198	-	342	292	180	-	-	06/17/40	KCT	100	2230	8	3
3456573.9	420658.0	89	44	159	-	315	266	160	-	8.2	08/17/67	KCT	103	2270	16	3
3454972.2	426566.2	64	28	18	-	298	24	27	-	7.7	08/14/68	KCF-KCT	269	2400	1	3
3449713.2	416543.8	69	39	82	-	338	105	78	-	7.5	10/14/66	KCT	200	2260	13	3
3452319.7	417439.3	87	24	153	-	284	37	275	-	7.5	08/14/68	KCT-TrD	265	2290	6	3
3451260.9	416875.5	128	81	420	-	348	620	475	-	7.4	08/12/68	KCT-TrD	300	2270	8	3
3451274.9	420481.6	84	54	189	-	310	292	219	-	7.5	10/09/67	KCF-KCT	168	2300	16	3
3449225.1	423088.2	86	21	23	-	284	42	45	-	7.5	10/09/67	KCF-KCT	369	2500	1	3
3450510.7	424530.7	141	76	425	-	329	627	470	-	-	06/27/40	KCF	260	2360	8	3
3450518.4	424554.7	125	71	403	-	327	590	455	-	7.5	08/12/68	KCF	261	2360	8	3
3449564.6	427055.0	70	21	11	-	289	15	16	-	7.8	10/01/67	KCF-KCT	250	2260	1	3
3445931.9	417908.0	43	33	43	-	267	54	40	-	7.8	10/14/66	KCF-KCT	335	2400	13	3
3446733.2	420442.0	56	29	18	-	273	33	26	-	7.6	10/09/67	KCF-KCT	333	2450	13	3
3446212.1	426579.6	76	16	15	-	282	16	23	-	7.8	09/05/67	KCF-KCT	320	2240	1	3
3452772.8	428770.0	69	26	47	-	289	14	87	-	7.9	09/01/67	KCF-KCT	112	2270	13	3
3448431.9	428408.6	77	17	16	-	284	19	24	-	7.6	09/05/67	KCT	235	2200	1	3
3451419.1	433503.4	91	18	14	-	329	13	27	-	7.6	08/28/67	QAl	33	2180	1	3
3445221.5	429781.8	51	30	27	-	278	36	30	-	7.9	09/01/67	KCF-KCT	335	2350	13	3
3444412.8	431307.0	66	22	25	-	270	30	39	-	7.7	09/01/67	KCF-KCT	259	2350	1	3
3444579.4	432519.1	50	27	33	-	281	36	28	-	7.6	09/06/67	KCF-KCT	365	2450	13	3
3441508.3	426563.5	68	14	15	-	230	16	24	-	6.9	07/12/61	KCF	145	2270	1	3
3441524.2	426571.7	67	17	13	-	251	18	21	-	7.8	07/21/67	KCF	145	2270	1	3
3439850.9	426700.2	72	16	9	-	278	13	14	-	7.6	08/28/67	KCF	135	2300	1	3
3443052.9	425947.7	97	17	26	-	337	29	31	-	7.9	07/21/67	KCF	140	2275	1	3
3439790.0	426991.1	47	20	17	-	220	18	21	-	-	07/27/40	KCF	120	2310	13	3
3439847.5	425144.7	69	23	30	-	279	36	38	-	7.9	08/17/67	KCF	325	2330	1	3
3443357.9	429222.2	94	68	440	-	307	585	422	-	7.8	09/01/67	KCF-KCT	400	2400	8	3
3440969.3	428647.6	33	25	63	-	276	43	34	-	7.8	08/28/67	KCF	240	2310	13	3
3442103.4	430120.4	68	18	12	-	266	15	17	-	7.8	09/01/67	KCF	220	2340	1	3
3439695.7	428622.0	54	38	272	-	290	323	231	-	8.2	08/24/65	KCF-KCT	445	2350	8	3
3489038.4	476232.2	525	8623	8678	4.0	243	86008	516	-	7.92	-	-	50	1720	11	4

Appendix 1 (cont). Chemical composition of shallow ground water.

Lat. (utm)	Long. (utm)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	pH	Sample date	Formation*	Sample depth (ft)	Land elevation (ft)	A	B
3486447.3	478555.1	252	82	169	3.0	218	270	461	-	8.06	-	-	140	1780	14	4
3486477.9	481874.7	359	128	334	2.0	228	174	980	-	7.62	-	-	85	1770	14	4
3481807.9	481909.8	229	96	143	3.0	258	167	454	-	7.98	-	-	200	1785	14	4
3482382.8	470168.3	189	62	114	1.0	362	156	236	-	8.30	-	-	40	1805	16	4
3474618.7	485095.1	185	118	91	2.0	288	474	205	-	8.12	-	-	100	1780	16	4
3472842.1	484211.2	188	115	192	2.0	304	465	367	-	8.08	-	-	-	-	16	4
3467640.1	484090.4	212	111	233	2.0	363	258	482	-	7.85		-	80	1860	14	4
3470852.8	478570.4	157	64	156	3.0	321	261	184	-	8.00	-	-	180	1860	16	4
3466054.5	474298.0	669	242	369	12.0	438	2040	639	-	7.77	-	-	150	1925	15	4
3473277.0	463395.5	268	97	243	4.0	214	161	735	-	7.72	-	-	90	1865	14	4
3472582.1	463000.0	452	152	363	4.0	202	192	1310	-	7.58	-	-	-	-	14	4
3472492.6	456795.1	181	50	391	1.0	313	284	573	-	7.85	-	-	-	-	6	4
3472543.4	457944.1	448	139	732	2.0	310	402	1622	-	7.60	-	-	90	1850	14	4
3471182.8	458583.7	536	177	744	3.0	292	386	1970	-	7.53	-	-	-	-	14	4
3469719.4	458540.9	385	124	386	5.0	192	131	1230	-	7.76	-	-	90	1905	14	4
3466993.9	459361.8	188	69	232	3.0	461	113	479	-	7.69	-	-	105	1920	14	4
3447778.0	448486.2	73	30	259	8.0	379	180	211	-	8.31	-	-	-	-	8	4
3465660.1	439390.4	90	41	113	3.0	297	128	161	-	8.39	-	-	60	1970	16	4
3468625.4	441035.1	212	89	422	4.0	399	318	712	-	8.13	-	-	100	1980	6	4
3469324.4	441864.6	498	185	1770	12.0	333	432	3380	-	7.55	-	-	85	1970	6	4
3487587.0	460072.1	560	263	978	13.0	206	462	2650	-	8.01	-	-	85	1905	14	4
3488019.6	460775.5	519	223	220	7.0	232	753	1060	-	8.03	-	-	240	1910	14	4
3493950.1	444024.8	280	192	284	2.0	293	225	976	-	8.07	-	-	60	1985	14	4
3495226.5	443836.2	921	491	7185	86.0	250	2070	11630	-	7.92	-	-	200	1990	6	4
3504994.6	437874.9	71	41	36	2.9	-	81	23	-	7.2	08/26/83	KCT	100	2199	15	5
3478405.7	440037.3	120	70	110	3.6	-	120	290	-	7.7	08/22/83	QLe-KCT	69	2080	14	5
3483898.1	471281.7	200	84	120	3.6	-	150	550	-	7.2	08/29/83	QLe-PLC	60	1770	14	5
3451852.4	482931.4	59	33	15	1.4	-	71	21	-	7.5	08/17/83	KCF	201	2220	15	5
3501147.3	423775.0	81	21	8	1.3	-	13	11	-	7.7	03/22/83	KCT	116	2190	2	5
3503698.2	436357.4	110	63	65	2.6	-	190	120	-	7.2	08/26/83	QLe	70	2095	15	5
3503930.5	466446.8	97	70	74	4.5	-	110	190	-	7.3	08/18/83	KCT	175	2095	14	5
3506040.3	473135.5	310	79	100	7.2	-	1100	61	-	7.4	08/18/83	PLC	238	2015	3	5
3488630.3	434539.1	61	16	7	1.0	-	29	8	-	7.8	08/22/83	KCT	276	2337	3	5
3492473.5	448922.5	94	37	24	1.5	-	22	46	-	7.2	08/23/83	QLe	100	1975	2	5
3495451.7	460572.5	46	40	340	14.0	-	440	160	-	7.5	08/30/83	PGPR	200	2015	7	5
3489657.0	458289.3	180	120	260	7.6	-	150	800	-	7.2	08/30/83	PGPR	99	1946	14	5
3488890.5	467033.5	100	62	52	4.0	-	110	150	-	7.4	08/29/83	PLC	80	1850	14	5
3488007.8	478544.8	280	120	270	3.8	-	610	640	-	7.1	08/29/83	QLe	28	1735	14	5
3474018.2	461716.1	580	230	860	6.0	-	400	2600	-	7.0	08/30/83	QLe-PLC	90	1876	14	5
3476006.1	472676.0	200	81	170	3.3	-	140	590	-	7.3	08/23/83	QLe-PLC	120	1832	14	5

Appendix 1 (cont). Chemical composition of shallow ground water.

Lat. (utm)	Long. (utm)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	pH	Sample date	Formation*	Sample depth (ft)	Land elevation (ft)	A	B
3470791.1	440117.0	85	38	140	5.8	-	42	270	-	7.6	08/24/83	QLe	74	1990	14	5
3470936.7	450830.4	270	150	590	6.1	-	180	1500	-	7.1	08/25/83	PGPR	30	1898	6	5
3465484.7	442235.9	140	150	340	8.7	-	470	650	-	7.5	08/25/83	QLe	52	1975	14	5
3459081.9	440943.5	230	110	330	13.0	-	220	930	-	7.3	08/24/83	QLe	80	2053	14	5
3470902.4	458618.5	410	120	380	5.0	-	130	1400	-	7.1	08/23/83	QLe-PLC	80	1900	14	5
3464112.9	455056.2	120	38	130	2.8	-	93	210	-	7.2	08/24/83	QLe	44	1983	14	5
3469760.5	484728.8	200	140	100	2.5	-	580	340	-	7.4	08/17/83	PLC	100	1845	15	5
3449438.4	464348.0	100	10	36	1.9	-	25	40	-	7.3	08/17/83	KCF	100	2138	2	5
3442665.7	443012.5	65	41	710	14.0	-	580	750	-	7.7	08/24/83	KCT-PGPR	270	2308	6	5
3490697.5	397432.9	55	17	9	0.9	-	13	12	-	7.9	08/22/83	KCT	213	2568	2	5
3502771.2	421055.1	83	39	24	-	375	52	34	0.4	7.2	05/01/69	KCT	152	2330	13	6
3503001.7	422537.4	96	62	2	-	27	194	61	0.4	7.5	05/01/69	KCT	159	2263	11	6
3503001.7	422537.4	95	60	32	2.0	326	179	68	7.1	7.8	06/22/79	KCT	159	2263	16	6
3502265.2	424211.1	111	71	34	-	190	353	87	0.4	7.6	05/01/69	KCT	113	2188	15	6
3502273.3	424195.0	143	67	32	-	298	231	152	3.4	7.6	07/22/75	KCT	113	2188	4	6
3504331.9	436965.5	210	67	52	-	301	590	27	0.4	7.7	08/22/69	P	-	-	3	6
3504994.7	437883.0	66	43	34	2.0	395	64	20	-	8.0	05/15/85	KCA	100	2199	13	6
3504986.5	437867.0	67	44	35	-	401	64	21	0.4	7.9	06/22/79	KCA	100	2199	13	6
3504986.5	437867.0	75	43	38	-	382	85	27	0.4	7.8	08/06/74	KCA	100	2199	13	6
3504986.4	437858.9	66	45	36	-	390	71	22	0.4	7.5	08/22/69	KCA	100	2199	13	6
3503655.8	441664.9	71	25	10	-	342	10	9	4.8	8.1	06/21/79	KCT	80	2265	1	6
3503655.8	441664.9	74	26	9	-	338	11	14	7.0	7.6	07/22/75	KCT	80	2265	1	6
3503663.6	441648.8	68	29	9	-	325	10	13	7.0	7.9	08/14/69	KCT	80	2265	1	6
3504515.9	443610.1	80	31	12	-	383	17	7	13.0	7.5	08/14/69	QLe	-	-	1	6
3501949.1	451044.0	80	25	7	-	350	11	7	0.4	7.4	08/14/69	KCT	-	-	1	6
3499540.7	459610.6	31	28	111	12.0	386	80	34	-	8.1	05/16/85	KCT	75	2100	5	6
3499540.9	459626.7	55	45	95	-	432	114	49	0.1	7.7	06/26/79	KCT	75	2100	13	6
3499540.8	459618.6	52	45	93	-	405	124	47	0.4	7.8	09/02/69	KCT	75	2100	13	6
3490286.1	416824.7	59	24	16	-	285	30	10	3.0	7.8	07/22/75	KCT	117	2379	1	6
3490277.9	416816.8	52	29	17	-	287	33	11	0.4	7.4	09/14/67	KCT	117	2379	13	6
3489809.7	407405.1	89	20	18	-	327	20	24	20.4	7.5	06/22/79	KCF-KCT	97	2445	1	6
3489817.8	407405.0	53	25	14	-	253	21	18	12.0	7.8	07/22/75	KCF-KCT	97	2445	13	6
3488726.9	410687.8	29	30	6	-	206	18	12	5.0	7.8	01/25/68	KCF-KCT	-	-	9	6
3491873.3	426884.4	54	26	19	-	293	31	10	0.4	8.0	06/22/79	KCF	100	2381	13	6
3491857.1	426876.5	49	33	15	-	268	32	19	13.5	7.8	09/08/69	KCF	100	2381	13	6
3494266.6	425528.3	84	16	8	-	318	12	12	0.4	7.3	09/08/69	KCF	160	2449	1	6
3488909.1	420457.1	52	28	30	-	279	67	14	0.4	7.9	09/14/67	KCT	120	2262	13	6
3496396.3	437780.1	84	54	38	-	384	101	67	4.9	7.3	08/19/50	QLe	66	2015	13	6
3497988.3	436952.0	92	59	54	-	417	140	58	16.6	-	03/15/60	P	90	2020	13	6
3494030.2	430781.0	67	42	31	-	345	80	24	0.4	7.5	09/16/69	KCT	245	2186	13	6

Appendix 1 (cont). Chemical composition of shallow ground water.

Lat. (utm)	Long. (utm)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	pH	Sample date	Formation*	Sample depth (ft)	Land elevation (ft)	A	B
3492909.7	430507.5	96	29	10	-	414	16	11	0.4	7.3	09/04/69	KCT	280	2175	1	6
3493634.3	430558.5	84	29	8	-	384	9	8	10.0	7.4	09/04/69	KCT	100	2170	1	6
3489146.9	437405.8	64	104	125	-	414	133	266	0.4	7.6	09/17/69	KCT	139	2185	16	6
3488278.1	437189.5	47	30	84	-	337	77	49	0.4	7.8	07/22/75	KCT	113	2177	13	6
3488330.9	437202.8	40	26	85	-	296	83	46	0.4	8.1	09/17/69	KCT	113	2177	13	6
3490108.3	445444.2	96	43	49	-	425	66	66	0.4	7.5	09/17/69	QAl	35	1938	13	6
3498455.5	461242.1	88	123	170	-	620	234	230	1.5	7.6	09/02/69	KCT	100	2138	16	6
3486432.0	454613.4	91	37	58	-	364	47	101	23.4	7.7	06/25/79	QLe	82	1914	13	6
3498354.9	466051.2	178	221	154	11.0	393	656	506	-	7.8	05/16/85	PLC	158	2073	12	6
3498354.9	466051.2	172	196	145	-	388	612	422	0.1	7.8	06/26/79	PLC	158	2073	12	6
3493646.5	478423.8	51	8	7	-	173	12	17	4.5	7.2	08/05/69	PLC-QLe	120	1800	1	6
3493627.7	478271.3	208	104	133	-	276	500	299	42.5	7.3	08/05/69	PLC-QLe	300	1810	16	6
3493440.6	477220.8	239	127	166	-	266	252	620	105.0	7.4	08/05/69	PLC-QLe	120	1825	14	6
3478405.7	440037.3	130	78	127	4.0	383	142	326	-	7.8	05/15/85	-	69	2080	16	6
3481500.0	458802.8	422	195	239	-	371	1360	445	0.4	7.4	10/06/70	QLe	127	1845	15	6
3481516.0	458794.7	82	63	90	-	510	4	170	0.4	7.7	10/06/70	QLe	39	1845	13	6
3481226.4	458554.2	560	189	283	-	398	1770	430	0.4	7.2	10/06/70	QLe	79	1850	3	6
3481323.9	459180.6	386	121	157	-	492	830	340	7.5	7.2	10/07/70	QLe	120	1835	4	6
3480119.3	459375.4	88	70	550	-	251	22	1070	0.4	7.3	06/09/71	PLC	50	1846	6	6
3480295.5	459085.9	203	53	250	-	364	197	530	12.0	7.1	06/10/71	PLC	60	1842	14	6
3479758.7	459938.2	281	125	600	-	520	332	1280	2.9	7.3	06/09/71	PLC	28	1815	6	6
3479910.8	459600.6	287	83	457	-	468	295	940	2.6	6.8	06/09/71	PLC	75	1841	14	6
3479403.5	458838.3	240	82	441	-	530	116	960	0.4	7.0	06/10/71	PLC	50	1842	6	6
3471789.5	454569.4	98	25	135	-	387	51	196	0.4	7.4	03/30/76	QAl	75	1850	16	6
3471645.2	454762.4	107	31	159	-	237	124	300	0.4	7.4	03/30/76	QAl	50	1855	14	6
3481931.2	471975.8	364	111	202	-	222	583	660	119.0	8.0	03/23/83	PLC-QLe	126	1815	2	6
3482589.0	471436.5	216	80	200	-	203	200	580	144.4	7.7	03/21/83	PLC-QLe	200	1805	14	6
3482589.0	471436.5	310	87	217	-	170	470	595	154.0	7.8	03/21/83	PLC-QLe	200	1805	14	6
3482597.0	471436.5	300	75	225	-	235	372	598	161.9	8.1	03/21/83	PLC-QLe	200	1805	14	6
3482597.1	471444.5	272	82	221	-	221	332	598	165.4	7.8	03/21/83	PLC-QLe	200	1805	14	6
3482597.0	471428.5	240	80	222	-	168	276	597	165.2	7.9	03/21/83	PLC-QLe	200	1805	14	6
3482605.1	471428.4	257	76	219	-	244	254	589	162.1	8.1	03/21/83	PLC-QLe	200	1805	14	6
3482605.1	471436.5	245	76	215	-	234	213	589	163.0	8.1	03/21/83	PLC-QLe	200	1805	14	6
3482580.8	471300.0	287	107	1580	-	920	92	2730	40.0	7.0	08/06/69	QLe	99	1805	6	6
3482007.2	469348.9	292	110	167	-	206	689	446	29.2	8.1	03/22/83	PLC-QLe	127	1808	16	6
3483914.1	471273.7	280	110	336	-	287	247	877	184.5	8.1	03/23/83	PLC-QLe	60	1770	14	6
3483972.4	472486.5	392	122	250	-	251	609	750	189.5	8.0	03/23/83	PLC-QLe	79	1805	14	6
3482526.6	472593.3	372	142	287	-	223	476	964	160.9	8.1	03/24/83	PLC-QLe	-	-	14	6
3483790.4	473313.9	444	108	194	-	182	997	541	77.3	7.9	03/23/83	PLC-QLe	100	1800	3	6
3484773.9	474017.9	532	168	170	-	196	1613	341	4.5	8.2	03/22/83	PLC-QLe	-	-	3	6

Appendix 1 (cont). Chemical composition of shallow ground water.

Lat. (utm)	Long. (utm)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	pH	Sample date	Formation*	Sample depth (ft)	Land elevation (ft)	A	B
3482998.1	474329.9	488	146	195	-	196	1268	492	35.3	8.1	03/22/83	PLC-QLe	120	1816	3	6
3481027.4	474136.0	184	71	148	-	216	149	467	134.7	8.2	03/23/83	PLC-QLe	120	1830	14	6
3475999.0	475481.0	162	55	128	3.0	240	134	382	-	7.8	05/14/85	QLe	98	1821	14	6
3475999.0	475497.1	226	50	173	-	228	182	499	98.0	7.4	06/26/79	QLe	98	1821	14	6
3475990.9	475481.1	323	78	237	-	205	258	810	134.0	7.4	07/23/75	QLe	98	1821	14	6
3476015.0	475472.9	182	69	123	-	243	143	426	40.0	7.3	12/06/72	QLe	98	1821	14	6
3475999.0	475489.1	202	66	141	-	228	151	466	68.0	7.4	12/10/71	QLe	98	1821	14	6
3482045.7	477766.6	234	64	158	4.0	235	377	390	-	7.8	05/14/85	QLe	103	1810	16	6
3482045.7	477758.6	194	58	166	-	218	144	480	124.8	7.6	06/26/79	QLe-PLC	103	1810	14	6
3470612.9	451499.7	202	84	452	-	353	326	870	9.0	7.5	03/30/76	QAl	24	1885	6	6
3457580.6	445259.5	91	22	18	1.0	377	23	18	-	7.8	05/15/85	KCT	65	2080	1	6
3457612.7	445243.3	98	20	12	-	355	25	22	15.0	7.5	07/23/75	KCT	65	2080	1	6
3457620.7	445243.3	94	24	15	-	365	20	17	18.5	7.6	09/22/69	KCT	65	2080	1	6
3470436.2	453775.8	94	31	184	-	245	134	306	0.8	8.1	03/30/76	QAl	65	1882	6	6
3470613.0	453743.0	284	58	520	-	333	380	1020	4.4	7.3	03/30/76	QAl	75	1880	6	6
3470612.0	453453.6	320	54	405	-	323	265	960	3.4	7.2	03/30/76	QAl	85	1885	14	6
3470702.0	455164.5	251	88	371	-	384	305	820	15.0	7.4	03/30/76	QAl	35	1880	14	6
3470862.8	455171.4	220	49	274	-	476	178	550	0.4	7.2	03/30/76	QAl	25	1890	14	6
3471027.5	454955.6	361	93	1090	-	499	1280	1350	36.0	7.1	03/30/76	PGPR	31	1880	6	6
3471009.5	469878.9	178	69	164	3.0	224	112	518	-	7.7	05/14/85	QLe	117	1862	14	6
3471020.2	469875.9	198	70	160	-	206	123	584	55.0	8.3	06/26/79	QLe	117	1862	14	6
3468881.0	474895.9	226	78	116	4.0	277	399	333	-	7.8	05/14/85	PLC	214	1885	16	6
3460531.2	475676.1	95	39	48	-	379	69	87	0.4	7.8	10/07/69	QAl	50	1993	13	6
3462533.4	478152.5	156	96	710	-	372	1020	710	3.5	7.5	10/07/69	QAl	-	-	8	6
3463247.0	488847.8	640	27	66	-	318	1290	164	0.4	7.2	03/27/69	QAl	130	1895	3	6
3455622.0	438126.4	81	26	28	-	386	14	27	5.0	7.4	08/15/69	KCT	90	2120	1	6
3455743.5	438391.2	95	27	18	-	414	14	19	5.5	7.6	08/15/69	KCT	82	2120	1	6
3456027.6	439153.8	97	28	20	1.0	423	18	25	-	7.9	05/15/85	KCA	85	2123	4	6
3456035.5	439137.7	110	25	23	-	433	20	27	15.0	7.6	06/25/79	KCA	85	2123	1	6
3456011.4	439129.7	104	29	18	-	399	15	43	10.0	7.6	08/07/74	KCA	85	2123	1	6
3454050.2	439120.7	56	36	493	-	311	462	463	5.0	7.4	08/15/69	P	90	2193	8	6
3444496.9	435554.2	46	29	37	-	281	32	34	3.5	7.5	09/06/67	KCT	360	2388	13	6
3447236.5	435222.9	48	30	21	-	285	24	21	3.0	7.6	09/05/67	KCT	216	2274	13	6
3443654.5	437467.4	58	41	448	-	307	479	388	3.0	7.7	09/06/67	KCF-KCT	450	2512	8	6
3445438.5	437692.8	64	24	19	-	287	19	24	8.5	7.8	09/06/67	KCF	450	2420	1	6
3446896.4	438258.2	70	19	11	-	299	4	19	0.4	7.6	05/13/69	KCT	190	2335	1	6
3453324.1	445395.4	20	27	443	-	580	36	425	0.4	7.8	05/22/69	KCT	150	2156	6	6
3450107.2	442862.4	60	23	18	-	282	15	20	12.0	8.0	06/25/79	KCT	177	2255	1	6
3450115.2	442862.3	87	11	11	-	282	16	17	21.0	7.7	07/23/75	KCT	177	2255	1	6
3450099.1	442862.4	62	23	18	-	294	13	24	0.4	7.7	05/22/69	KCT	177	2255	1	6

Appendix 1 (cont). Chemical composition of shallow ground water.

Lat. (utm)	Long. (utm)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	pH	Sample date	Formation*	Sample depth (ft)	Land elevation (ft)	A	B
3446575.6	441078.7	75	11	6	-	249	12	12	10.0	7.6	05/13/69	KCT	190	2358	1	6
3444485.7	450047.5	108	14	12	-	353	16	22	24.0	7.7	07/23/75	KCF-KCF	120	2147	1	6
3444501.7	450039.4	49	23	287	-	353	181	259	0.4	7.6	08/05/69	KCF-KCF	120	2147	8	6
3443922.0	450766.9	85	12	6	-	283	12	7	20.5	7.6	08/05/69	KCF-KCF	58	2148	1	6
3453478.2	460429.8	89	14	17	-	305	14	26	17.0	7.5	07/24/75	KCF-KCF	80	2083	1	6
3453470.2	460437.9	108	25	23	-	423	19	29	15.5	7.8	08/25/69	KCF-KCF	80	2083	1	6
3451158.9	454942.9	63	17	11	-	229	18	22	19.0	7.9	05/22/69	KCF	150	2172	1	6
3451424.7	453190.6	146	31	40	-	412	42	121	15.0	7.5	05/26/69	KCF	60	2076	1	6
3451306.9	459991.0	64	26	22	-	285	16	33	9.0	7.8	08/25/69	KCF	180	2189	1	6
3449236.6	461012.3	67	22	20	-	289	17	25	11.5	7.5	08/25/69	KCF	220	2268	1	6
3444643.2	452470.5	89	18	35	-	316	12	66	6.8	7.5	07/02/70	KCF	-	-	1	6
3444410.8	452520.7	86	19	37	-	303	12	68	7.0	7.4	08/06/69	KCF	35	2070	1	6
3444374.6	453448.0	86	19	35	-	306	13	67	6.5	7.4	08/06/69	KCF	45	2087	1	6
3445406.1	452620.9	88	19	35	-	315	12	65	8.5	7.4	07/02/70	KCF	30	2069	1	6
3445982.3	458800.8	82	11	10	1.0	278	11	16	-	8.0	05/15/85	KCA	200	2292	1	6
3445982.3	458800.8	76	17	10	-	285	19	15	11.0	7.9	06/25/79	KCA	200	2292	1	6
3454501.6	466452.7	75	14	17	-	253	22	28	12.0	7.4	09/15/69	KCF-KCF	-	-	1	6
3455633.7	471879.6	70	21	21	1.0	244	36	43	-	8.0	05/15/85	KCT	110	2188	1	6
3455657.9	471887.4	75	23	26	-	256	38	48	25.0	7.8	06/26/79	KCT	110	2188	1	6
3455641.7	471879.5	63	20	14	-	244	20	26	12.0	7.6	08/08/74	KCT	110	2188	1	6
3449455.6	464336.9	78	19	16	-	306	15	23	11.0	7.6	12/11/67	KCF	124	2145	1	6
3449357.9	468738.7	65	27	25	-	299	24	36	0.4	7.6	09/15/69	KCF	120	2252	13	6
3449455.6	475250.9	70	17	10	-	270	20	16	5.0	7.5	05/14/69	KCF	190	2231	1	6
3447659.7	470135.0	57	14	12	-	203	12	25	13.0	7.6	09/15/69	KCF	175	2272	1	6
3454614.8	482898.9	81	19	9	-	287	8	24	19.5	7.6	09/23/69	KCF	99	2127	1	6
3454986.3	484044.1	68	21	6	-	268	11	7	28.5	7.6	09/23/69	KCF	114	2087	1	6
3454337.1	485109.9	88	27	14	-	328	53	20	0.4	7.3	09/23/69	KCF	100	2070	1	6
3451852.4	482931.4	77	35	19	-	264	108	30	4.0	7.8	04/29/69	KCF	201	2148	1	6
3447985.2	483343.0	61	30	10	-	234	79	12	2.5	8.0	04/29/69	KCF	225	2184	1	6
3445800.2	478736.5	38	28	13	-	232	24	17	0.4	7.6	12/11/67	KCF	201	2275	13	6
3445236.7	481311.4	58	26	8	1.0	290	8	10	-	7.9	05/15/85	-	210	2254	1	6
3442098.2	436028.8	47	30	10	-	260	18	18	3.0	7.6	09/06/67	KCF	430	2570	13	6
3441524.2	451059.7	81	19	26	-	295	26	36	14.0	7.6	12/11/67	KCF	89	2175	1	6
3443119.5	453454.8	86	20	37	-	310	15	70	6.5	7.3	08/06/69	KCF-KCF	60	2096	1	6
3442409.9	459069.8	89	11	17	-	283	13	37	7.0	7.6	07/23/75	KCF	80	2163	1	6
3442413.8	459045.4	77	20	22	-	299	15	35	8.0	7.5	08/06/69	KCF	80	2163	1	6
3439708.0	472743.0	44	22	9	-	222	10	12	8.0	7.8	07/22/65	KCF	-	-	1	6
3439701.3	474710.7	53	20	10	-	246	11	14	1.5	7.2	08/10/65	KCF	-	-	1	6
3442082.0	476922.2	48	27	14	-	256	17	19	2.5	7.7	04/28/69	KCF	225	2334	13	6
3442483.7	480580.8	52	31	9	-	285	17	19	1.5	8.1	05/14/69	KCF	235	2238	13	6

Appendix 1 (cont). Chemical composition of shallow ground water.

Lat. (utm)	Long. (utm)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	pH	Sample date	Formation*	Sample depth (ft)	Land elevation (ft)	A	B
3442491.7	480580.7	40	32	12	-	259	23	20	0.4	8.3	06/26/79	KCF	235	2238	9	6
3442519.3	480628.6	57	28	11	-	278	23	18	2.0	7.8	07/24/75	KCF	235	2238	1	6
3490917.5	380359.8	54	34	28	-	218	105	25	17.0	7.8	03/08/66	KCT	-	-	13	6
3489853.8	381019.5	54	30	22	-	287	40	21	5.0	7.7	03/08/66	KCT	-	-	13	6
3488878.6	380697.9	69	27	19	-	300	33	30	0.4	7.1	09/26/67	KCT	127	2474	1	6
3491389.5	392002.8	43	24	13	-	224	19	17	5.5	7.6	01/23/68	KCF-KCT	105	2446	13	6
3491381.6	392019.0	44	24	14	-	228	19	17	8.0	7.7	06/21/79	KCF-KCT	105	2446	13	6
3491389.5	392002.8	46	24	13	-	232	17	17	8.0	7.6	07/22/75	KCF-KCT	105	2446	13	6
3488722.3	386213.1	49	29	17	-	248	37	20	11.5	7.9	01/23/68	KCF-KCT	122	2481	13	6
3489401.8	386746.1	42	29	17	-	224	25	21	13.0	7.6	03/13/69	KCF-KCT	-	-	13	6
3489191.3	396489.7	52	31	20	-	267	36	25	8.8	7.8	06/21/79	KCT	-	-	13	6
3489191.3	396489.7	54	31	17	-	268	37	25	9.0	7.7	07/22/75	KCT	-	-	13	6
3489199.4	396489.6	50	35	18	-	275	44	25	5.5	7.4	09/26/67	KCT	-	-	13	6
3489452.2	398923.0	49	27	21	-	242	24	31	10.5	7.7	09/22/67	KCT	128	2480	13	6
3489699.5	402666.6	59	31	19	-	283	30	33	0.4	7.6	03/06/68	KCF	244	2588	13	6

* - Stratigraphic unit: P - undifferentiated Permian; PLC - Clear Fork; PGPR - Pease River; TrD - Dockum; KCT - Trinity; KCF - Fredericksburg; QLe - Leona Formation; QAl - Quaternary alluvium

A - Hydrochemical facies: 1 - Ca-HCO_3; 2 - Ca-Cl; 3 - Ca-SO_4; 4 - Ca-mixed-anion; 5 - Na-HCO_3; 6 - Na-Cl; 7 - Na-SO_4; 8 - Na-mixed-anion; 9 - Mg-HCO_3; 10 - Mg-Cl; 11 - Mg-SO_4; 12 - Mg-mixed-anion; 13 - mixed-cation-HCO_3; 14 - mixed-cation-Cl; 15 - mixed-cation-SO_4; 16 - mixed-cation-mixed-anion

B - Data source: 1 - Work Projects Administration (1941); 2 - Willis (1954); 3 - Pool (1972); 4 - Richter and Kreitler (1985); 5 - Lee (1986); 6 - Texas Natural Resources Information System computerized and open-file data

Appendix 2. Conversion factors from mg/L to meq/L.

Constituent		Multiply	By	To obtain
Calcium	Ca^{+2}	mg/L	4.99×10^{-2}	meq/L
Magnesium	Mg^{+2}	mg/L	8.23×10^{-2}	meq/L
Sodium	Na^{+1}	mg/L	4.35×10^{-2}	meq/L
Potassium	K^{+1}	mg/L	2.55×10^{-2}	meq/L
Sulfate	SO_4^{-2}	mg/L	2.08×10^{-2}	meq/L
Chloride	Cl^{-1}	mg/L	2.82×10^{-2}	meq/L
Bicarbonate	HCO_3^{-1}	mg/L	1.64×10^{-2}	meq/L

Appendix 3 Depths to surface casing, to cement plugs, and to base of fresh water in 113 exploration holes that were abandoned longer than 25 years ago. Data were compiled from records at the Railroad Commission of Texas for identification of test site.

ID	Year Abandoned	Surface Casing/ Well Depth (ft)	Depth to Plugs (Sacks of Cement @ ft) First Plug	Second Plug	Third Plug	Depth to Base of Fresh Water*	Lease
1	1952	457/7011	10@top	50@465	100@ 900	250	W.F. Williams
2	1954	254/3504	35@top			200	J.F. Kennemer
3	1956	252/6610	?@100	?@ 640	?@5240	250	Llano Cty S.L.
4	1955	596/6875	5@top	25@ 620	25@6600	250-300	Llano Cty S.L.
5	1951	294/6580	15@top	50@ 290	50@ 350	250-300	Llano Cty S.L.
6	1958	302/6503	15@sc			250-300	E.M. Baker
7	1950	167/5792	5@ 10	30@1050	35@5670	150	J.W. Johnson
8	1957	315/3460	3@top	12@3103?	30@3440	150	J.W. Johnson
9	1957	327/3486	3@top	12@ 310?	30@3440	150-200	Johnson "A"
10	1952	218/5505	Cement in surface casing			150-250	J.W. Johnson
11	1955	163/5410	5@top	10@ 163	20@2000	275	Meadow Est.
12	1951	288/5402	10@top	20@2000	20@3000	200	J.E. Kaparik
13	1956	215/5537	2@top	20@ 225		200-300	J.W. Johnson
14	1959	350/5278	5@top	50@ 360	25@1800	200-350	J.W. Johnson
15	1960	164/5430	5@top	10@ 160	15@1800	200	J.W. Johnson
16	1955	217/5948	Cement at 217			175-300	E. Straach
17	1958	?/5729	10@top	25@bsc	25@5729	150-478	Llano Cty S.L.
18	1954	421/6220	15@top	20@3825	40@6284	150-175	Llano Cty S.L.
19	1952	712/7015	5@top	10@ 698	25@7015	200-350	M.M. Compton
20	1954	213/7060	3@top	23@ 254	20@7015	250-300	A. Mayer Est.
21	1957	218/5610	25@sc	25@ 600	25@5200	150-200	P.H. Demere
22	1934	0/ 714	10@?			150-200	J. Willeke
23	1952	486/5802	10@top	50@ 500	25@5250	200	Blaylock
24	1954	496/5515	?@110	?@3636	?@5500	200	O.J. Bubenik
25	1959	623/5563	125@750			200	H. Byrd
26	1961	163/5801	5@top	120@?		200	Boys Ranch
27	1953	215/5860	15@top	25@1200	35@5200	200	E.H. Jones
28	1950	514/5770	100@top	25@1940	50@2550	200	E.H. Jones "A"
29	1960	112/5785	5@top	50@ 132	25@5785	200-250	M.D. Bryant
30	1952	103/5612	190@500	60@5600		250	W.E. Schulkey
31	1952	235/3566	10@top	25@3566		150-200	Wash. Cty. S.L.
32	1955	473/6245	10@top	?@ 540	?@5421	300-400	C.D. Atkins
33	1957	454/6855	10@25	35@ 504	35@5319	400	C.D. Atkins
34	1954	490/7010	20@520	15@6500		300-400	C.D. Atkins
35	1950	224/7015	25@250	25@4990		350-450	C.D.&C.L. Atkins
36	1948	479/7329	20@top	10@ 485	65@6710	450	C.D. Atkins
37	1951	278/5758	10@top	25@ 270	25@920	400-500	Jacobs
38	1958	500/5574	25@525			300-500	L. Anson
39	1951	422/5850	5@top	25@ 445	30@5850	300-500	K. Harris
40	1961	420/4842	10@top	15@ 450	25@4840	300-500	M.H. Griffith

Appendix 3 (cont).

ID	Year Abandoned	Surface Casing/ Well Depth (ft)	Depth to Plugs (Sacks of Cement @ ft) First Plug	Second Plug	Third Plug	Depth to Base of Fresh Water*	Lease
41	1953	300/6003	50@450	38@4885	25@5400	300-500	W.A. West
42	1950	330/6000	15@top	10@ 330		300-500	W.A. West
43	1954	400/5975	5@top	25@ 400		400-450	P.E. Jemeyson
44	1954	315/6257	not	reported		-400	J.W. Johnson
45	1960	431/5725	10@top	10@ 415	15@4950	-400	Johnson
46	1956	352/5522	10@top	40@ 400		-400	H. Holiman
47	1954	265/5405	10@top	25@ 265	25@4770	-400	J.W. Johnson
48	1954	274/6350	25@296			-400	J.W. Johnson
49	1957	180/6066	25@240	25@3420		150-400	Johnson Est.
50	1949	270/6524	10@top	25@ 300		150-400	J. Scherz
51	1954	224/6402	25@top	25@ 245	80@6250	150	Johnson
52	1958	323/5500	10@top	50@ 325	100@2400	150	Wash. Cty. S.L.
53**	1955	100/6212	5@top	5@ 100	20@4880	150	Wash. Cty. S.L.
54	1952	208/6105	10@top	20@ 220	20@2100	150	Wash. Cty. S.L.
55	1958	102/5241	10@top	25@ 102	10@4800	150-328	J.D. Eaton
56	1956	97/6462	unknown			150	N. McGowan
57	1957	243/6302	10@top	25@ 320	25@2250	150-328	F.R. Butler
58		456/	Halliburton ret. @ 5928			150-200	Nasworthy
59	1954	180/5110	not	reported		150-200	T. Nasworthy
60	1950	397/6225	50@390	35@5279		200	J.N. Brannan
61	1953	370/7169	15@top	50@ 385	50@1600	200	W.R. Schwartz
62	1956	349/5307	55@top	15@ 400	20@3350	200	W.R. Schwartz
63	1954	175/3400	?@175	?@2675	?@3350	200	D.W. Hair
64	1954	129/6500	10@150	15@2048	15@5000	200-328	Parsons
65	1954	143/7152	5@top	25@ 150	25@2300	150	Stanford
66	1955	240/5950	10@ 12	50@ 310	50@5020	150	R. Walling
67	1959	233/5825	?@ 48	?@ 141	?@1700	150-350	A.W. McGowan
68	1961	224/5048	5@top	30@ 280	40@1000	150-350	J. Simcik
69	1960	156/4994	25@top	25@ 150		150-350	A. Hennig
70	1949	273/6149	5@top	20@ 320	25@ ?	150	R.C. Jones
71	1956	189/5649	3@top	25@ 229		350	A.J. Schniers
72	1961	157/4740	10@top	20@ 200	20@4410	250-375	J.D. Robertson
73	1952	230/4799	?@top	?@ 250	?@4799	250-375	J.W. Green
74	1961	303/4780	10@top	15@ 303	25@4400	300-350	J.W. Green
75	1950	121/4844	20@top	30@ 800		200-350	M. Kent
76	1953	333/5442	25@top	75@ 400	100@1950	200	Malone "209"
77	1961	136/4665	10@top	25@ 136	25@3990	150-200	Rust
78	1953	150/5010	10@150	15@1500		150-200	Rust
79	1957	253/4992	5@top	25@ 425		150	C. Malone Est.
80	1955	175/5914	?	?	?	150	G.F. Rust
81	1948	280/5821	10@top	?@ 280		150	G.F. Rust
82	1953	203/4565	5@top	15@ 115	15@4015	150	G.F. Rust
83	1953	210/4700	10@210	35@2000		200-250	S.V. Holik
84	1960	204/4230	10@top	25@ 240	25@2000	200-250	O.B. Sparks
85	1953	216/4677	10@top	25@ 216	56@1800	200-250	J.H. Halfman
86	1949	240/5330	25@248	25@4600		200-325	F.J. Holik
87	1954	249/4866	10@top	25@ 260	25@4821	250-375	Wood
88	1959	170/4640	25@195			250-325	F.J. Holik

Appendix 3 (cont).

ID	Year Abandoned	Surface Casing/ Well Depth (ft)	Depth to Plugs (Sacks of Cement @ ft) First Plug	Second Plug	Third Plug	Depth to Base of Fresh Water*	Lease
89	1959	247/4400	?@top	15@ 240	50@4400	325	Hohensee
90	1956	247/5255	15@top	?@ 275	35@4400	225-325	P. Hohensee
91			10@187	20@4682		225	M.E. Davis
92	1951	205/4769	25@top	and	bottom	225	M.E. Davis
93	1954	216/4875	Cement			200-225	G.O. Davis
94	1956	259/5254	5@top	10@ 259	25@4500	200	Davis
95	1959	137/4609	20@180	80@2240	50@3630	150	J.D. York
96	1959	170/4590	25@195			200	C.S. Callahan
97	1961	172/4796	10@top	15@1500	10@2800	200-225	J.J. Schiller
98	1949	216@5775	not	reported		325	T.C. Wood
99	1961	167/4836	30@240	50@1920	30@4275	350	M. Lock
100	1961	260/4805	10@top	15@ 275	25@1983	350	N.W. Little
101	1960	300/5357	5@top	10@ 315	20@1850	200-350	F.A. Braden
102a	1957	184/4352	?@ 50			150-200	J. Dusek
102b	1959	168/5028	10@top	40@ 168		150-200	J. Dusek
103	1957	117/3910	15@top	35@ 135	75@3900	100-375	R.G. Fuessel
104	1949	100/4780	not	reported		150	J. Molde
105	1954	192/5292	Cement			150-200	L.V. Braden
106	1957	203/4889	10@top	25@ 237	75@1600	150-250	O.M. Garvin
107	1954	148/4930	5@top	10@ 140	50@1700	150	E.L. Ford
108	1955	206/5110	5@top	10@ 220	28@1665	150-325	F.G. Rogers
109	1961	302/5183	?@top	?@ 330	?@1820	250-325	K.L. Morrison
110	1955	264/5315	5@top	10@ 217	20@1850	200-325	K.L. Morrison
111	1957	175/4600	10@top	25@ 246	25@1800	417	T.H. Williams
112	1960	105/4300	3@top	25@ 120	50@1500	150	S.D. Childress

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* As established by Texas Department of Water Resources; depth values approximated from data reported by Richter and Kreitler, 1985.

** Test well 22.