OF-WTWI-1983-4

IDENTIFICATION OF RECHARGE-DISCHARGE AREAS OF THE PALO DURO BASIN, TEXAS PANHANDLE

by

R. K. Senger

B. C. Richter

Prepared for the
U. S. Department of Energy
Office of Nuclear Waste Isolation
under contract no. DE-AC-97-83WM46615

Bureau of Economic Geology
W. L. Fisher, Director
The University of Texas at Austin
University Station, P. O. Box X
Austin, Texas 78712

332FI Hydrology F.4. Identification of Recharge-Discharge Areas (5.7.1)

This report presents the preliminary results of research to identify the recharge and discharge areas of the major aquifers in the Palo Duro Basin. Recharge has been investigated by studying the isotopic compositions of surface and shallow ground waters in New Mexico and Texas. Discharge studies have focused on identifying the source of the brine discharged in springs and seeps along the outcrop of Permian rocks east of the Caprock Escarpment.

Recharge

Hydrogen and oxygen isotopes in shallow ground water commonly reflect the isotopic composition of precipitation. They can be used to describe the range of isotopic composition of potential recharge water to the deep basin aquifer. Water samples for isotopic analysis were collected from shallow municipal water wells along a 300-mile long traverse from the Manzano Mountains in New Mexico, across the High Plains and Rolling Plains to the Texas-Oklahoma state line. The generalized east-west section of the Palo Duro Basin along the traverse is shown in figure 1.

Location and isotopic composition of the water samples (Fig. 1) are given in Table 1. The δD values fall well within the expected range of meteoric water in this area (fig. 2), as reported by Lawrence and Taylor (1972). The δD and $\delta^{18}O$ values show a general increase from west to east (Fig. 1), reflecting the increase in elevation to the west and the dominance of precipitation from the Gulf of Mexico in the east, and the Raliegh fractionation of precipitation as it moves farther from the Gulf of Mexico.

The isotopically lightest ground water is found at the highest elevations, near the Manzano Mountains in New Mexico. An example is the ground-water sample from the Mountainair city well (elevation 6545 ft) with δD and $\delta^{18}O$ values of -82‰ and -11.46‰, respectively. Similar values are reported from the Roswell Basin further to the south, indicating that recharge occurs in the mountain massifs to the west (Hoy and Gross, 1982). Near the Pecos River, shallow ground water from alluvium near Santa Rosa City (elevation 4600 ft) shows δD and $\delta^{18}O$ values of -55‰ and -7.30‰, respectively, reflecting the isotopic composition of meteoric water at that altitude (Hoy and Gross, 1982). In contrast, a deep ground-water sample from the Santa Rosa City Well #3 shows significantly lighter isotopes, indicating that recharge to the confined San Andres Formation occurs farther to the west, at higher elevations.

Along the High Plains, the δD and $\delta^{18}O$ values of ground waters generally increase from west to east, reflecting the overall decline in elevation. However, a water sample collected from the Dockum Group (at -816 feet) in a well in Tulia, Swisher County, shows unusually low δD and $\delta^{18}O$ values of -68‰ and -9.22‰, respectively, for this particular area. A similar isotopic composition was found in a water sample collected previously from the same well and depth, while a water sample from the Ogallala Formation yielded a $\delta^{18}O$ value of -7.8‰ (Bassett, unpublished data). The difference in isotopic composition suggests that deeper ground water in the Dockum Formation originates farther to the west at higher elevations, and that ground waters of the Dockum and Ogallala formations do not undergo significant mixing.

Shallow ground water east of the Caprock Escarpment generally has the highest δ values for the oxygen and hydrogen isotopes. Kreitler and

Bassett (1983) reported similar $\delta^{18}O$ values for shallow ground water in the area but obtained lower δD values due to problems in sampling and methods.

A plot of $\delta^{18}O$ vs. δD (Fig. 3) shows that the data from shallow ground water fall close to the meteoric water line. Minor isotopic enrichment of the ground water is probably due to evaporation and other isotopic modifications occurrring during recharge.

Discharge

The brine emission areas of the Rolling Plains region (Fig. 4) were discussed in S.C.R. Section 5.7.1.3, submitted to DOE in October, 1982. A tentative conclusion reached in that report was that the saline springs immediately east of the Caprock Escarpment resulted from shallow meteoric ground waters dissolving bedded salt, not from deep-basin brine discharge. The results of subsequent ground-water flow modeling (BEG, 1983a) suggest that deep-basin brines could be discharging in the Rolling Plains. In order to resolve the question of the source of the saline surface water of the Rolling Plains, additional salt springs have been sampled by TBEG and testhole samples and chemical analyses obtained from the U.S. Geological Survey and the U.S. Army Corps of Engineers. The chemical and isotopic analyses of all of these waters are shown in Tables 2, 3, and 4.

The weight ratios of bromide to chloride (Br/Cl) and sodium to chloride (Na/Cl) have been used to differentiate between brines of different origins (Whittemore et al., 1981). Brines formed by meteoric water dissolving bedded halite have Br/Cl weight ratios less than 4×10^{-4} and Na/Cl weight ratios near 0.64 ($\pm$ 0.04). Deep-basin brines (originally of meteoric origin) commonly have Br/Cl weight ratios greater than 25 x 10^{-4} and Na/Cl weight ratios of less than 0.59. According to the Br/Cl and Na/Cl ratios, three groups of water can be distinguished from the brine emission areas: (1) group A has Br/Cl ratios less than 4 x 10^{-4} and Na/Cl ratios greater than 0.61, and is interpreted as representing a meteoric water that has dissolved bedded salt; (2) group B has ratios that fall between those of groups A and C (though generally closer to A), and is thought to represent mixing between those groups; and (3) group C has Br/Cl ratios greater than 25 x 10^{-4} and Na/Cl ratios less than 0.59, and is interpreted as representing deep-basin brine (Fig. 5). Plots of other chemical constituents (Ca, Mg, K, I) versus chloride support the division into three groups. Ratios of the chemical constituents (e.g., Br/Cl) of oil field brines from the Palo Duro and Midland Basins closely resemble the ratios from Group C water, supporting the deep-basin origin interpretation. The exact source of the brine (Palo Duro or Midland Basin) has not been determined.

The oxygen and hydrogen isotopic composition of salt springs, test-holes from the North Croton Creek area, and deep-basin brines is shown in Figure 6. The isotopic values from Group A waters plot within the typical range of meteoric water, supporting the interpretation that dissolution of halite by meteoric water accounted for the salinity. Though isotopic values were not available for most Group C waters, those values obtained plot on a line which includes deep-basin brine values and meteoric-water values as its endpoints, suggesting a dilution of deep-basin brine by meteoric water. The Br/Cl and Na/Cl ratios of these waters indicate that mixing occurred with fresh water, rather than with halite-dissolution brine.

A plot of ^{18}O versus depth for Group C waters (Fig. 7) shows a significant enrichment in ^{18}O with depth. This, and a sharp increase in chloride with depth (Fig. 8), serves as additional evidence for a deep-basin origin for Group C brine. Discharge of a local meteoric ground water that obtained its salinity by dissolving halite further to the west would be expected to have ^{18}O values close to or lighter than values for meteoric water in the area.

The geographic distribution of samples belonging to groups A, B, and C is shown in Figure 4. Group A waters dominate in the northern and western parts of the study area and are found in most of the salt springs. Group C waters are restricted to testhole samples (25-117 feet deep) from the North Croton and Croton/Dove/Haystack Creek areas in the south and one sample from the Elm Fork site in Harmon County, Oklahoma. Group B waters are found between Group A and Group C-dominated areas, supporting the mixing interpretation drawn from the intermediate position found in the water chemistry.

A plot of chloride versus depth for individual testholes in the North Croton Creek area shows a sharp increase in chloride concentrations within 25 to 70 feet below land surface (Fig. 8). This could reflect that the deep-basin brine is present at a relatively shallow depth and is separated from an overlying fresh-water body by a thin mixing zone. A plot of Br/Cl ratios versus depth for four brine-emission areas (Fig. 9) shows that deep-basin brine is nearest to the land surface in the southern part of the study area. Deep-basin brine has not been identified in testholes down to 300 feet below land surface at the Jonah/Salt Creek and Middle Pease River sites. To the south, deep-basin brine has been encountered within 300 feet, and approaches land surface in the North Croton Creek area.

Potentiometric surface maps of the Wolfcamp aquifer from McNeal (1964) and Smith (BEG, 1983b) have been combined in order to produce a map that covers the entire brine-emission study area (Fig. 10). McNeal's data have been changed drastically at the northern boundary of his map in order to obtain a fit with Smith's data. The correction is supported by Bentley's potentiometric surface map of the Wolfcamp aquifer (Bentley, 1981) and the assumption that McNeal's abnormally low head values in northern Stonewall and Kent Counties may have resulted from pressure data affected by oil production along the Matador arch. The potentiometric surface mapped in Figure 10 should be treated as a working hypothesis until a map with better control is available.

Comparison of the composite Wolfcamp potentiometric-surface map (based on fresh-water heads) with land-surface elevation and the potentiometric surface map for the unconfined aquifer (Figs. 10 and 11) supports the conclusions based on the plot of Br/Cl ratios versus depth: fresh-water heads for the brine aquifer are below both the land surface and the water table in the north, and above, or near, them in the south. This same geographic relationship has been found between the fresh-water heads of the San Andres brine aquifer and the surface elevation and water table. A computer-generated head-difference map for the Wolfcamp and unconfined aquifers (BEG, 1983c) indicates the same trend, with head differences approaching zero in southeastern Cottle County (Fig. 12). Conversion of fresh-water heads to salt-water heads by a density correction would probably lower the brine potentiometric surfaces below land surface over the entire area, but might still allow upward flow into the unconfined aquifer on a local basis where joints and fractures serve as flow paths for the deep-basin brine.

Mason-Johnston and Associates (1955) reported that artesian heads on brines in fractures and solution openings 50 to 100 feet below Dove Creek Salt Flat (Fig. 4) were up to 7 feet above the salt flat surface. Thus, if mixing of a deep-basin brine with a halite-dissolution brine occurs below the salt flat (as suggested by the water chemistry), the potential for discharge of deep-basin brine does exist.

The deep-basin brines have been identified in areas where the hydraulic heads of the brine aquifers are close to either surface elevation or the water table, or where joints and fractures serve as flow paths for the brine. Most of the salt-springs found on the Rolling Plains do not coincide with any of these likely deep-basin brine emission areas, and their waters do not exhibit deep-basin brine characteristics. However, the chemistry of some of the salt springs (Group B) indicates that they may be mixtures of halite-dissolution brine with small amounts of deep-basin brine. Halite-dissolution brine may mask deep-basin brine characteristics in some of the samples, especially those in which additional mixing with fresh water dilutes the brine to relatively low salinity values. Though deep-basin brines have been identified within the study area, determining the source of the brine (whether from the Palo Duro or Midland Basin) will require continued study.

References

Bassett, R. L., Bentley, M. E., and Simpkins, W. W., 1981, Regional ground-water flow in the Panhandle of Texas, a conceptual model, in Gustavson, T. C., and others, Geology and geohydrology of the Palo Duro Basin, Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 81-3, p. 102-107.

Bentley, M. E., 1981, Regional hydraulics of brine aquifers, Palo Duro and Dalhart Basins, Texas, in Gustavson, T. C., and others, Geology and geohydrology of the Palo Duro Basin, Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 81-3, p. 93-101.

Bureau of Economic Geology, 1983a, Characterization Status Report, Section 5.6.2 Relationships Among Hydrogeologic Units: Submitted to DOE 2-28-83 under contract number DE-AC97-83WM46651, p. 1-8.

Bureau of Economic Geology, 1983b, Characterization Status Report, Section 5.6.3 Potentiometric Levels: Submitted to DOE 2-28-83 under contract number DE-AC97-83WM46651, p. 9.

Bureau of Economic Geology, 1983c, Characterization Status Report, Section 5.7.2 Principal Ground-Water Flowpaths: in preparation for DOE contract number DE-AC97-83WM46651.

Hoy, R. N., and Gross, G. W., 1982, Stable isotopes in the Roswell Groundwater Basin: New Mexico Water Research Institute, Report 146.

Kreitler, C. W., and Bassett, R. L., 1983, Chemical and isotopic composition of saline ground water and saline springs in the Rolling Plains east of the Ogallala Escarpment, _in_ Gustavson, T. C., and others, Geology and geohydrology of the Palo Duro Basin, Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology Geological Circular.

Lawrence, J. R., and Taylor, H. P., Jr., 1972, Hydrogen and oxygen systematics in weathering profiles: Geochimica et Cosmochimica Acta, v. 36, p. 1377-1393.

Mason-Johnston and Associates, 1955, Dove Creek Salt Study, Stonewall County, Tx: Report for Brazos River Authority, Tx, and Ambursen Engineering Corporation, Houston, Tx.

McNeal, R. P., 1964, Hydrodynamics of the Permian Basin: American Association of Petroleum Geologists Memoir 4, p. 308-326.

Whittemore, D. O., Basel, C. L., Galle, O. K., and Waugh, T. C., 1981, Geochemical identification of saltwater sources in the Smokey Hill River Valley, McPherson, Saline and Dickinson Counties, Kansas: Kansas Geological Survey, Final Report to the U.S. Army Corps of Engineers, 78 p.

List of Tables

Table 1

$\delta^{18}O$, δD for selected water wells in
New Mexico and Texas Panhandle

Sample location of municipal wells	Formation	Depth (ft)	$\delta^{18}O$ (%)	δD (%)
1. Mountainair	Yeso	215	-11.46	-82
2. Santa Rosa #3	San Andres	620	-10.89	-82
3. Santa Rosa	Alluvium	62	-7.30	-55
4. Fort Sumner	Artesia Gp.	201	-7.52	-57
5. Tucumcari #12	Dockum	330	-6.96	-50
6. Tucumcari #10	Dockum	310	-4.89	-47
7. Clovis #29	Ogallala	360	-7.04	-52
8. Friona #9	Ogallala	310	-8.01	-56
9. Dimmit #1	Ogallala	375	-6.95	-52
10. Tulia #14	Dockum	816	-9.22	-68
11. Kress	Ogallala	300	-5.49	-44
12. Silverton	Ogallala	200	-5.63	-41
13. Turkey	Permian/Alluvium	174	-6.42	-44
14. Estelline	Permian/Alluvium	62	-5.36	-42
15. India Creek	Permian/Alluvium	20	-6.33	-46
16. Poducah	Permian/Alluvium	260	-6.16	-41
*17. Tulia #14	Dockum	816	-10.0	
*18. Tulia #7	Ogallala	200?	-7.8	
*19. Silverton	Ogallala	181	-5.3	
*20. Plainview #14	Ogallala (Base)	325	-8.6	
*21. Floydada	Ogallala (Base)	312	-7.6	
**22. Quitaque	Permian/Alluvium	192	-6.5	
**23. Quitaque	Permian/Alluvium	?	-6.8/-6.9	
**24. Turkey	Permian/Alluvium	110	-5.3/-6.2	
**25. Flomot	Permian/Alluvium	?	-6.1/-6.7	
**26. Matador	Permian/Alluvium	293	-6.0	

*Bassett (unpublished information)
**Kreitler and Bassett (1983)

Table 2. Group A brines

County	Sample no.	Date collected	Sample type and depth (ft)	Temp. (°F)	pH	Na	K	Ca	Mg	HCO_3	SO_4	Cl	Br	Na/Cl	Br/Cl x 10^{-4}	$\delta^{18}O$	δD
Hall	1	6-17-69	Spring	-	7.50	5,230	22.	1,010	306	196	3,350	8,250	-	.63	-	-	-
"	3a	4-01-80	"	53	8.00	23,166	57.2	1,835	341	124	4,805	32,225	6.3	.72	1.95	-4.7	-
"	3b	10-29-69	"	-	6.60	13,100	78.	1,350	548	100	4,520	20,800	-	.63	-	-	-
"	3c	10-29-69	"	-	6.80	8,775	35.	905	1,156	408	6,700	13,200	-	.66	-	-	-
Childress	4a	3-28-83	"	71.	7.52	25,100	35	1,440	295	111	4,750	38,995	9.98	.64	2.56	-	-
"	4b	3-28-83	"	68.	7.30	14,730	28.7	1,304	245	150	4,000	23,400	5.96	.63	2.55	-	-
"	5	3-24-59	"	-	7.60	5,990	-	1,030	213	110	2,860	9,500	-	.63	-	-	-
Cottle	8	6-14-83	"	76.	8.55	7,630	10.9	1,050	230	99	3,450	11,860	3.30	.64	2.78	-	-
"	9a	3-29-83	"	78.	8.19	12,340	19.3	1,270	194	104	3,940	19,320	6.08	.64	3.15	-	-
"	9b	3-29-83	"	75.	8.10	13,860	19.	1,270	223	121	3,960	21,624	6.72	.64	3.11	-4.97	-40
"	9c	3-29-83	"	72.	7.50	11,800	18.7	1,250	178	121	3,750	18,257	5.53	.65	3.03	-5.83	-41
"	10a	3-29-83	"	71	7.31	12,430	22.1	1,230	243	130	3,960	19,497	6.17	.64	3.16	-5.90	-45
"	11a	4-02-80	"	65	7.40	9,790	30.5	1,165	238	138	3,431	14,210	4.00	.69	2.81	-	-
"	11b	3-30-83	"	63	7.30	7,380	16.8	979	196	170	3,160	11,465	4.43	.64	3.86	-	-
"	11c	3-30-83	"	70	7.40	3,910	11.	782	156	164	2,410	6,253	2.39	.63	3.82	-5.56	-39
"	11d	3-30-83	"	70	7.51	3,350	10.	748	149	173	2,150	5,384	2.11	.62	3.92	-5.64	-40
Kent	17	11-02-82	"	70	7.30	39,900	87.9	1,750	608	43	5,540	63,000	11.	.63	1.75	-6.11	-49
"	18	11-01-82	"	70	6.90	103,000	281	667	1,200	27	6,710	158,000	26.8	.65	1.70	-5.79	-44
Childress	19	5-06-81	Well 48.3-100.3	70	8.40	12,740	36.4	1,380	290	175	4,050	19,450	7.50	.65	3.86	-	-
"	20	5-16-81	" 127.0-132.5	68	8.10	23,890	46.2	1,650	360	114	4,810	37,400	13.00	.64	3.48	-	-
"	21	8-16-74	" 150-224.8	-	-	44,550	114.	2,430	154	-	5,220	68,480	17.30	.65	2.53	-	-
"	22	6-11-81	" 22.1-44.5	-	-	20,660	34.9	1,700	397	-	4,710	32,720	9.30	.63	2.84	-	-
"	23	8-13-74	" 165-185.	-	-	34,850	55.4	1,910	562	-	5,220	55,960	13.70	.62	2.45	-	-
"	24	10-14-81	" 32-47.8	-	-	16,970	35.3	1,570	372	-	4,500	27,550	7.70	.62	2.79	-	-
"	25	10-14-81	" 116.-135.	-	-	13,360	33.2	1,310	303	-	4,110	21,400	5.50	.62	2.57	-	-
"	26	10-07-81	" 20.-28.3	-	-	21,420	39.5	1,660	380	-	5,010	34,460	9.30	.62	2.70	-	-
Cottle	27	3-25-81	" 86.-173.	64.5	7.50	10,541	26.5	1,291	255	165	3,650	16,000	6.50	.66	4.06	-4.74	-
"	28	3-19-81	" 103.1-151.5	66.	7.80	10,439	20.6	1,292	249	127	4,040	16,000	7.00	.65	4.37	-	-
"	29	3-07-79	Spring	-	-	15,010	25.	1,550	322	-	4,440	23,480	6.80	.64	2.90	-	-
"	30	4-07-81	Well 49.8-52.8	-	-	11,010	23.4	1,300	272	-	3,990	17,190	5.70	.64	3.32	-	-
Kent	31	8-30-64	" 173-400	71	6.90	20,676	72.7	1,496	349	66.5	4,073	32,000	5.70	.65	1.78	-	-
"	32	9-14-64	" 307-357	70.5	6.70	52,590	153.8	1,294	621	58.	5,084	79,970	13.10	.66	1.64	-	-
"	33	7-16-64	" 0-175	70.	6.10	91,044	169.2	769	428	32.	6,837	135,820	19.60	.67	1.44	-	-
"	34	8-03-64	" 44-53	-	6.00	55,400	91.	913	415	39.	5,397	84,470	17.50	.66	2.07	-	-
"	35	10-06-64	" 519.5-602	-	5.60	122,604	183.	1,382	522	26.	4,375	189,916	21.60	.65	1.14	-	-
"	36	2-16-65	" 100	-	6.10	98,952	280.	1,343	1,390	46	6,938	151,962	21.2	.65	1.40	-	-
"	37	2-16-65	" 300	-	6.00	116,620	264	1,020	1,254	43.	6,344	179,694	35.00	.65	1.95	-	-
"	38	8-26-64	" 100-400	71	6.60	111,085	283	1,225	521	68.	6,632	168,454	25.90	.66	1.54	-	-
"	39	9-02-64	" 2-190	71	6.70	82,525	290	1,669	1,048	86.	6,252	129,160	27.40	.64	2.12	-	-
"	40	9-01-64	" 0-93	71	7.00	38,734	104	1,626	466	46.	5,575	60,027	11.80	.65	1.97	-	-
"	41	2-02-65	" 360	-	6.40	74,687	209	1,393	996	54	7,617	115,342	19.4	.65	1.68	-	-
"	42	2-02-65	" 460	-	5.90	118,244	225	982	1,469	48.	1,918	188,000	9.30	.63	.49	-	-
"	43	9-27-64	" 401.5-525	68	6.60	103,460	285	1,283	843	96.	6,391	158,895	27.10	.65	1.71	-	-
"	44	5-25-65	" 500	70	6.30	122,808	95	1,079	265	32.5	5,659	187,824	11.90	.65	.63	-	-
"	45	10-21-64	" 424-603	71	6.20	73,060	79.8	1,439	288	77.	4,139	113,524	10.00	.64	.88	-	-
"	46	10-20-64	" 260-410	71	5.60	121,200	158	2,136	398	12.	2,964	187,200	48.00	.65	2.56	-	-
"	47	10-08-64	" 340	70	6.30	114,050	144	2,171	480	15.	3,257	182,530	-	.62	-	-	-
"	48	3-25-66	" 206-299	65	5.90	124,836	1,794	925	1,163	38.	7,211	192,708	26.70	.65	1.39	-	-

Table 3. Group B brines

County	Sample no.	Date collected	Sample type and depth (ft)	Temp. (°F)	pH	Na	K	Ca	Mg	HCO_3	SO_4	Cl	Br	Na/Cl	Br/Cl x 10^{-4}	$\delta^{18}O$	δD
Hall	2	1-22-69	Spring	-	7.40	10,000	33.	2,400	750	182	2,780	19,800	-	.51	-	-	-
Harmon	6a	9-01-82	"	-	6.70	116,000	219.	1,050	1,600	71.8	3,570	187,000	92.2	.62	4.93	-5.63	-43
"	6b	9-01-82	"	-	6.55	115,000	118.	1,130	1,630	43.7	3,550	185,000	89.6	.62	4.84	-5.51	-43
Beckham	7	9-01-82	"	70	7.50	39,900	134.	2,120	1,050	118.	4,870	64,200	52.6	.62	8.19	-6.17	-52
Cottle	10b	3-29-83	"	70	7.30	8,630	20.2	996	198	140	3,430	14,357	5.2	.60	3.62	-	-
King	12a	-	"	80	6.80	15,480	36.	1,414	307	131	3,829	24,560	14.00	.63	5.70	-	-
"	12b	3-31-83	"	71	7.38	3,350	15.	903	202	127	2,820	5,732	5.19	.58	9.05	-	-
"	12c	11-03-82	"	64.5	7.30	2,290	15.2	822	204	126	2,720	3,680	5.46	.62	14.84	-5.97	-41
"	13	12-03-66	"	-	7.00	30,000	126.	1,330	764	116.	3,470	48,300	-	.62	-	-	-
"	14	11-02-82	"	68	7.10	75,400	102.	2,040	651	36.	4,340	114,000	36.9	.66	3.24	-5.65	-40
"	15	6-14-83	"	69	7.30	23,070	36.2	1,720	335	78	5,040	35,380	16.2	.65	4.58	-	-
Stonewall	16	6-14-83	"	72	6.70	100,700	277	2,350	1,770	25.	4,200	156,400	13.	.64	8.31	-	-
Childress	49	6-19-81	Well 197-249	68	7.30	112,000	220	1,950	750	71.6	2,670	175,100	70.	.64	4.00	-	-
"	50	6-18-81	" 249-300	68	7.50	73,300	227	2,250	770	79.3	3,000	116,000	65.	.63	5.60	-	-
"	51	9-02-81	" 25.7-37.0	-	-	9,310	18.3	1,390	295	-	3,840	15,590	4.2	.60	2.69	-	-
Stonewall	52	5-27-65	" 360	70.	6.90	61,150	374.	2,100	1,580	36.	4,270	102,000	-	.60	-	-	-
"	53	9-21-64	" 297-560	-	6.70	44,300	119.	2,120	482	204	5,300	69,000	30.	.64	4.35	-	-
"	54	10-09-64	" 213-300	68	6.20	120,000	477.	2,875	1,450	69	3,785	188,000	145.	.64	7.71	-	-
"	55	3-07-66	" 276-491	69	5.60	117,300	377.	3,640	1,180	34	2,018	191,000	153.4	.61	8.03	-	-
"	56	6-30-67	" 0-80	70	6.20	96,760	407.	2,300	1,730	25.	3,545	159,100	9.9	.61	.62	-	-
Kent	57	2-18-65	" 185	-	6.00	116,523	276	1,416	1,000	30	4,900	182,700	59.3	.64	3.25	-	-
"	58	10-19-64	" 201-300	68	6.20	116,570	226	3,080	852	82	2,368	187,240	122.	.62	6.52	-	-
"	59	2-17-65	" 200	-	6.30	117,320	514	3,309	2,194	102	2,170	191,500	235.	.61	12.27	-	-
"	60	9-01-64	" 295-489	73	6.20	119,900	357	1,882	1,098	56	3,429	188,243	86.3	.64	4.58	-	-
"	61	9-30-64	" 366-495	70	6.00	115,920	518	2,460	4,272	38	2,640	190,800	179.	.61	9.38	-	-
"	62	3-24-66	" 329-415	68	5.00	116,640	359	2,628	975	8.	2,760	182,400	102.	.64	5.59	-	-
"	63	6-20-63	" 29	-	-	13,583	77	1,675	555	104	3,951	22,535	-	.60	-	-	-
King	64	3-02-66	" 170-374	66	6.20	120,680	762	1,885	1,522	94	3,322	192,072	269.4	.63	14.03	-	-

Table 4. Group C brines

County	Sample no.	Date collected	Sample type and depth (ft)	Temp. (°F)	pH	Na	K	Ca	Mg	HCO_3	SO_4	Cl	Br	Na/Cl	Br/Cl x 10^{-4}	$\delta^{18}O$	δD
King	65	5-15-79	Well 82	66	7.30	12,000	220	1,100	930	140	5,700	20,000	140.	.60	70.00	-	-
"	66	5-08-79	" 80	69	6.40	60,000	1,300	3,400	7,200	190	1,300	130,000	860.	.46	66.15	-.3	-
"	67	5-15-79	" 52	68	7.20	7,000	170	1,500	900	100	3,000	15,000	100.	.47	66.67	-	-
"	68	5-15-79	" 70	67	6.60	38,000	200	1,400	8,500	30	6,700	81,000	510.	.47	62.96	-3.9	-
"	69	5-15-79	" 97	66	7.00	26,000	100	1,400	4,400	92	7,100	51,000	320	.51	62.75	-4.6	-
"	70	5-15-79	" 80	68	6.70	30,000	380	1,300	5,100	110	9,100	61,000	420	.49	68.85	-	-
"	71	5-16-79	" 59	66	6.70	25,000	410	2,000	4,300	74	5,000	49,000	290	.51	59.18	-4.9	-
"	72	5-16-79	" 38	69	6.80	14,000	320	1,000	3,200	82	8,900	26,000	160	.54	61.54	-	-
"	73	5-16-79	" 52	67	6.80	23,000	130	420	6,400	100	15,000	45,000	280	.51	62.22	-6.8	-
"	74	5-17-79	" 85	68	6.50	55,000	950	3,100	7,000	260	3,800	110,000	770	.50	70.00	+.1	-
"	75	5-17-79	" 110	69	6.20	97,000	1,500	2,400	12,000	100	2,900	190,000	1,100	.51	57.90	-	-
"	76	5-08-79	" 94	69	6.60	28,000	750	3,900	5,800	160	1,300	69,000	610	.41	88.41	-1.9	-
"	77	5-08-79	" 90	67	6.90	13,000	320	4,700	1,700	100	830	32,000	240	.41	75.00	-	-
"	78	5-09-79	" 75	69	6.80	16,000	390	3,200	3,000	180	1,900	37,000	230	.43	62.16	-1.9	-
"	79	5-15-79	" 65	67	6.50	28,000	150	2,200	3,900	200	4,900	54,000	350	.52	64.81	-	-
"	80	5-15-79	" 100	67	6.50	48,000	730	2,400	7,000	150	5,000	98,000	650	.49	66.33	-.14	-15
"	81	5-16-79	" 75	67	6.70	29,000	710	2,100	5,200	190	5,200	60,000	400	.48	66.67	-	-
"	82	5-16-79	" 109	67	6.40	53,000	960	3,300	8,400	170	3,900	110,000	760	.48	69.09	-.7	-
"	83	5-16-79	" 65	68	6.10	60,000	1,200	2,100	15,000	54	3,000	140,000	920	.43	65.71	-	-
"	84	5-16-79	" 72	69	7.00	6,800	230	1,800	1,200	250	2,700	16,000	110	.42	68.75	-4.3	-
"	85	5-18-79	" 90	67	6.40	30,000	390	10,000	4,300	80	1,500	77,000	500	.39	64.94	-	-
"	86	5-08-79	" 117	69	7.00	11,000	310	3,700	1,100	74	1,900	24,000	200	.46	83.33	-6.9	-
"	87	5-09-79	" 84	68	6.80	33,000	44	3,000	6,800	180	2,900	78,000	570	.42	73.08	-.5	-
Stonewall	88	5-11-79	" 32	64	7.10	9,500	160	970	900	64	4,500	16,000	94	.59	58.75	-	-
"	89	5-10-79	" 86	67	7.20	10,000	150	460	1,000	110	2,800	17,000	91.	.59	53.53	-	-
"	90	5-11-79	" 42	63	6.90	24,000	290	1,700	2,900	60	5,000	48,000	280	.50	58.33	-3.9	-
"	91	5-10-79	" 76	64	7.00	13,000	240	960	1,500	100	6,100	23,000	150	.57	65.22	-	-
"	92	5-10-79	" 52	64	7.00	13,000	280	370	3,800	72	5,000	27,000	160	.48	59.26	-5.2	-
"	93	5-10-79	" 105	68	7.00	22,000	260	1,600	1,900	110	5,200	41,000	200	.54	48.78	-4.08	-34
"	94	5-09-79	" 74	70	6.40	40,000	820	3,800	5,500	230	15	84,000	490	.48	58.33	-2.93	-27
"	95	5-27-65	" 170	-	6.50	103,200	825	11,070	3,700	32	687	188,000	-	.55	-	-	-
"	96	2-18-65	" 365	-	5.30	78,045	628	23,716	8,809	14	245	185,130	994.6	.42	53.72	-	-
"	97	2-18-65	" 100	-	5.80	82,600	716	24,034	9,100	18	3,733	195,000	1,034	.42	53.03	-	-
"	98	5-27-65	" 400	-	4.40	61,240	774	10,415	2,853	-	1,211	122,000	-	.50	-	-	-
"	99	5-27-65	" 600	-	4.00	61,860	807	10,220	2,990	-	1,212	122,400	-	.51	-	-	-
"	100	10-12-64	" 382-625	70	7.00	13,200	243	2,680	423	29	2,600	24,700	77.30	.53	31.30	-	-
"	101	10-14-64	" 318-503	70	6.30	15,613	164	2,740	640	44	3,120	28,000	91	.56	32.50	-	-
"	102	5-27-65	" 350	71	3.40	54,300	662	5,100	6,530	-	2,300	111,000	-	.49	-	-	-
"	103	10-15-64	" 255-361	67	5.40	24,200	332	3,053	1,590	6	3,750	44,000	166	.55	37.73	-	-
"	104	3-01-66	" 198-397	69	5.20	29,700	555	2,700	3,200	10	4,300	58,500	213.6	.51	36.51	-	-
"	105	3-06-66	" 260-370	69	5.00	25,000	400	2,300	3,470	8.5	4,740	49,500	161.	.51	32.53	-	-
"	106	3-04-66	" 296-475	67	6.30	11,200	130	1,060	2,000	30	7,080	20,000	83.40	.56	41.70	-	-
Kent	107	2-18-65	" 463	-	5.70	108,840	788	9,600	2,400	48.5	6,254	190,284	500.5	.57	26.30	-	-
Harmon	108	10-25-80	" 11.9-558	-	-	27,360	154	8,020	1,860	-	1,830	58,560	335	.47	57.21	-	-

List of Figures

Figure 10a&b. Potentiometric surface map of the Wolfcamp aquifer in the brine-emission study area compared to 10a: the water table and 10b: surface elevation. The Wolfcamp potentiometric surface map is a comilation of McNeal's (1964) and Smith's (BEG, 1983b) potentiometric surface maps.

Figure 11. Head map of the unconfined aquifers that overlie the evaporite sequences in the Palo Duro Basin (Bassett et al., 1981).

Figure 12. Computer-generated head-difference map for the Wolfcamp and unconfined aquifers (BEG, 1983c).

Figure 1

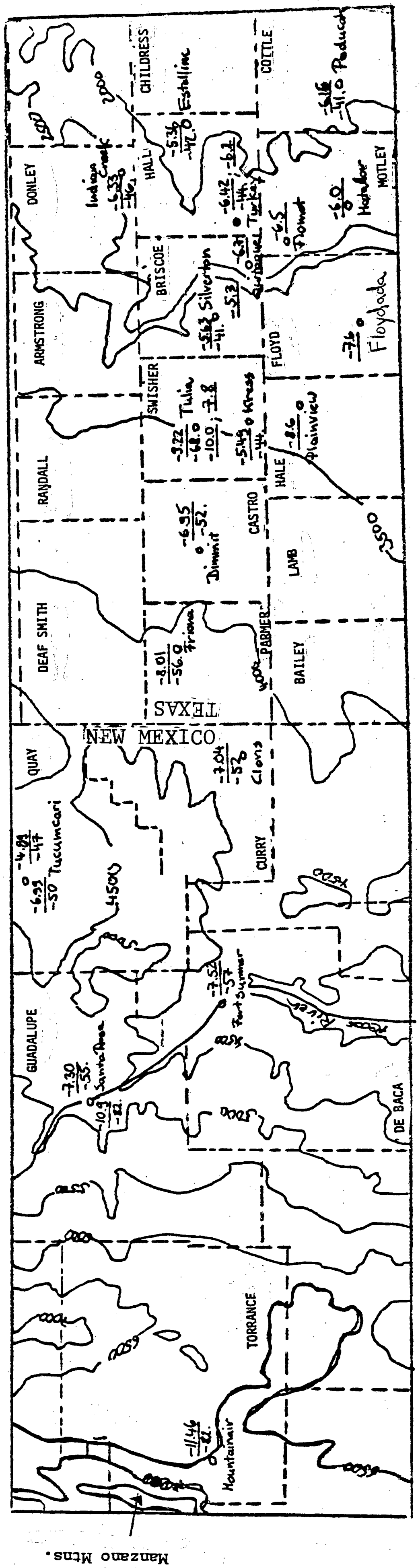
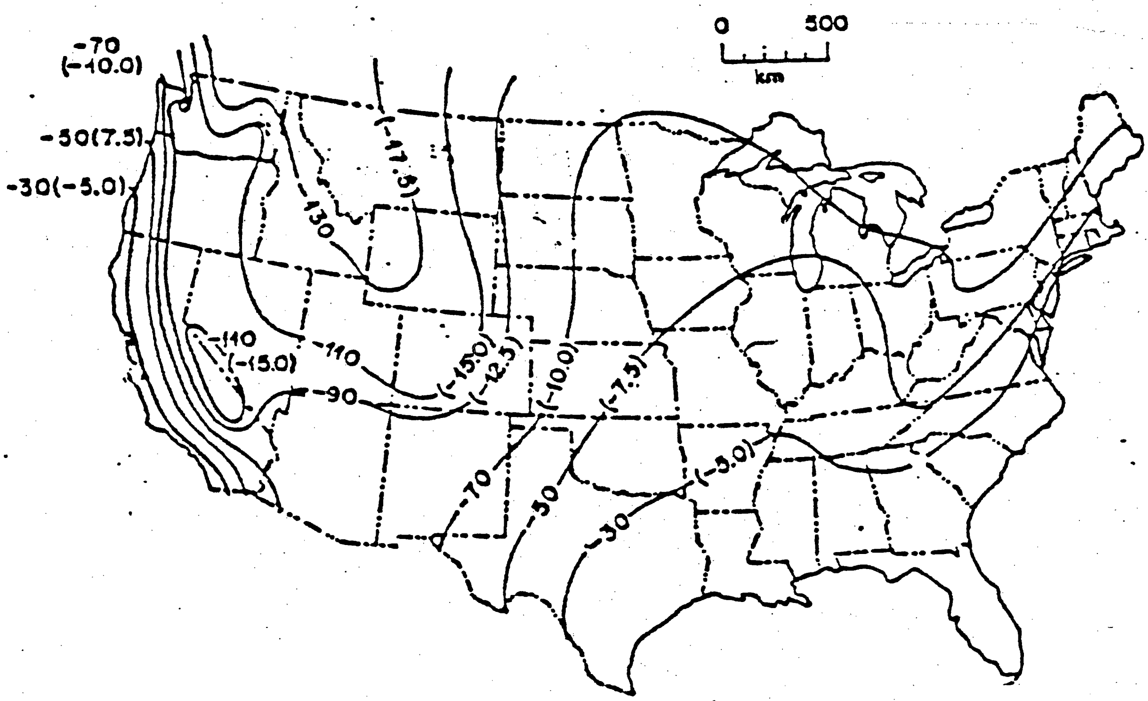
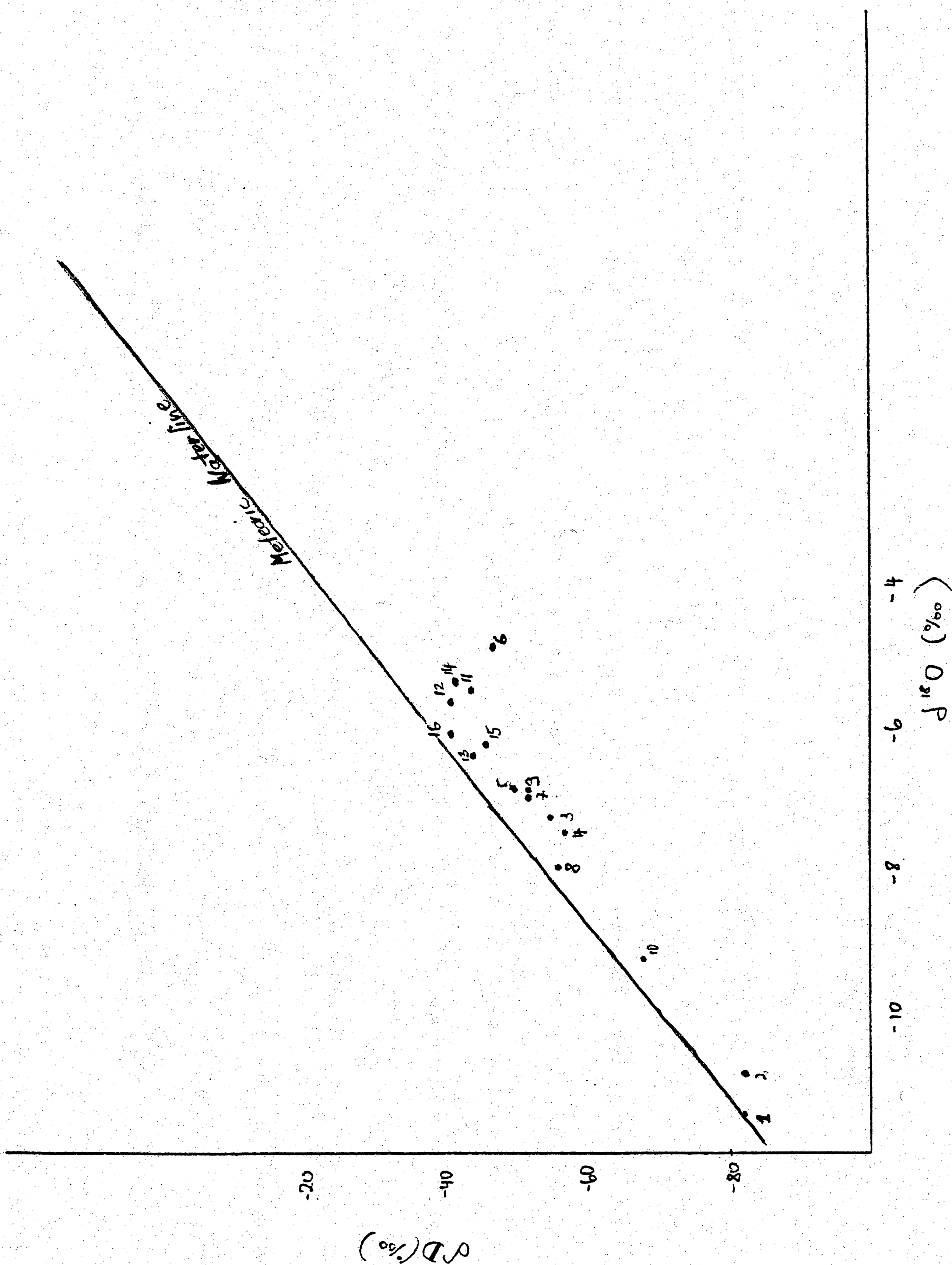

CHILDRESS
COTTLE
DONLEY
HALL
MOTLEY
ARMSTRONG
BRISCOE
FLOYD
SWISHER
RANDALL
HALE
CASTRO
LAMB
DEAF SMITH
PARMER
BAILEY
TEXAS
NEW MEXICO
QUAY
CURRY
GUADALUPE
DE BACA
TORRANCE
Estelline
Paducah
Silverton
Floydada
Tulia
Kress
Plainview
Dimmitt
Friona
Clovis
Tucumcari
Fort Sumner
Santa Rosa
Mountainair
Manzano Mtns.

Figure 2



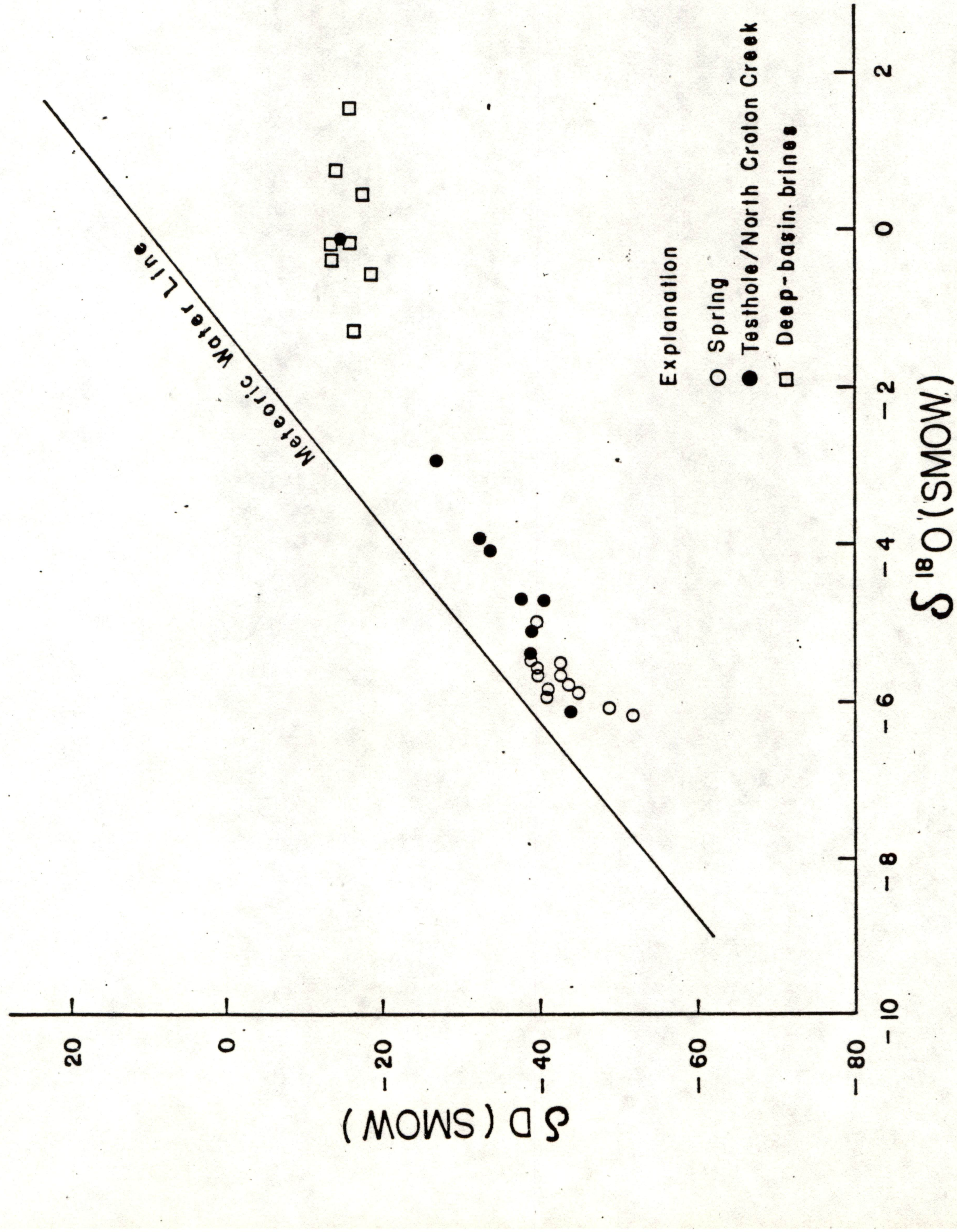
0
500
km
-70
(-10.0)
-50(7.5)
-30(-5.0)
-130
(-17.5)
-140
(-15.0)
-110
-90
(-15.0)
(-12.5)
(-10.0)
(-7.5)
70
50
30
(-5.0)

Figure 3



See separate file for figures 4 and 5

Figure 6



Meteoric Water Line
Explanation
Spring
Testhole/North Croton Creek
Deep-basin brines
δ¹⁸O (SMOW)
δD (SMOW)
20
0
-20
-40
-60
-80
-10
-8
-6
-4
-2
0
2

Figure 7

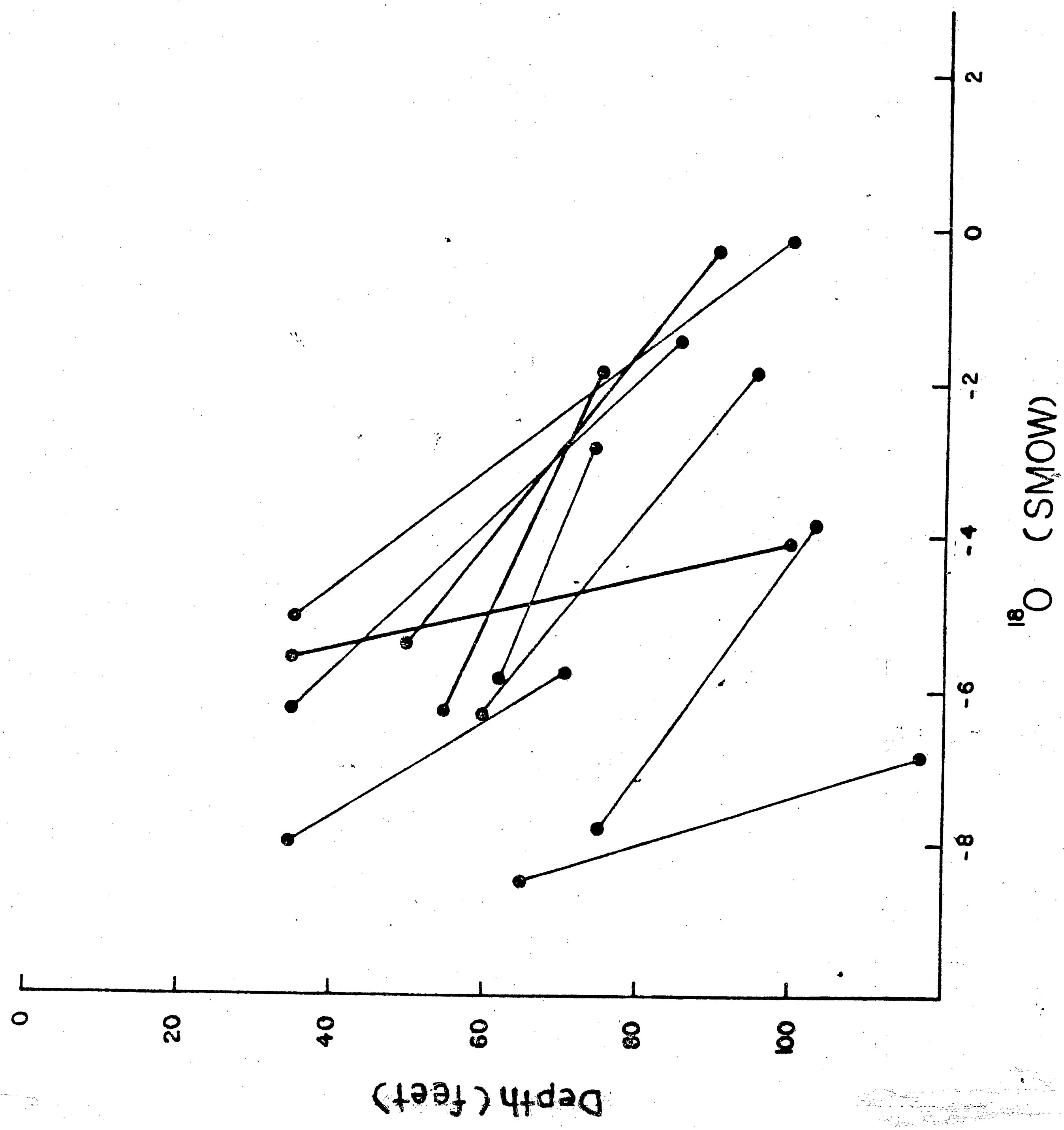


Figure 8

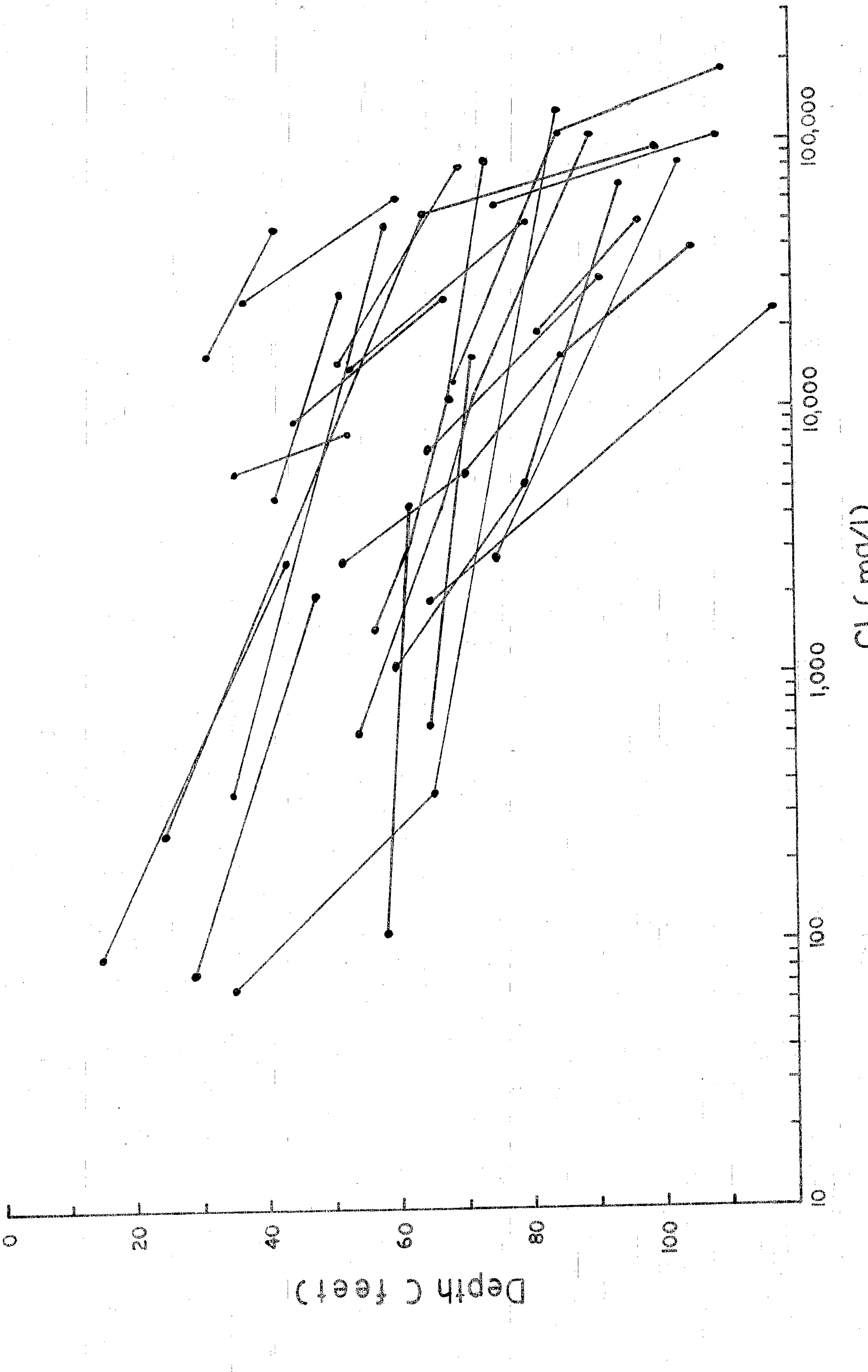
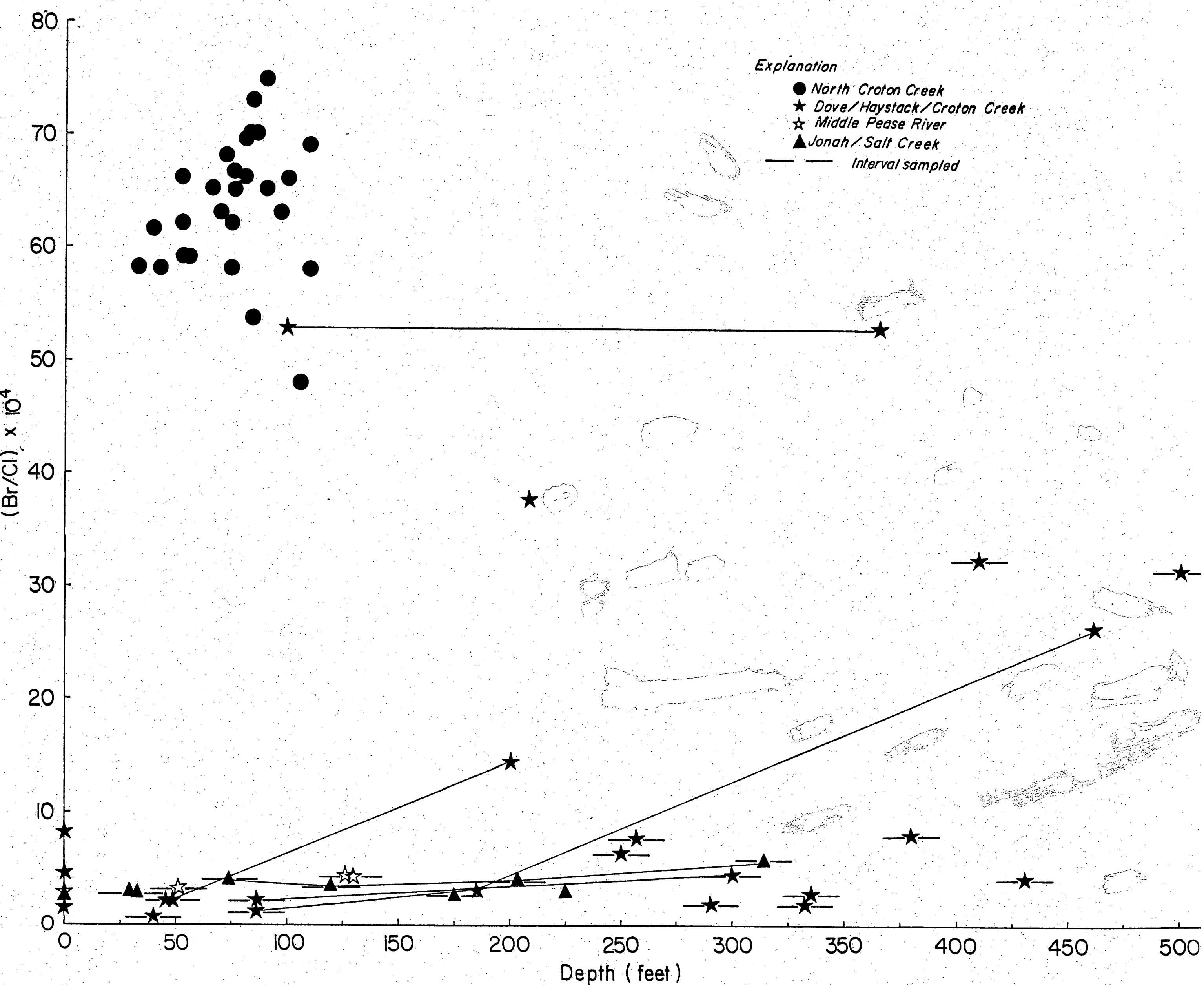
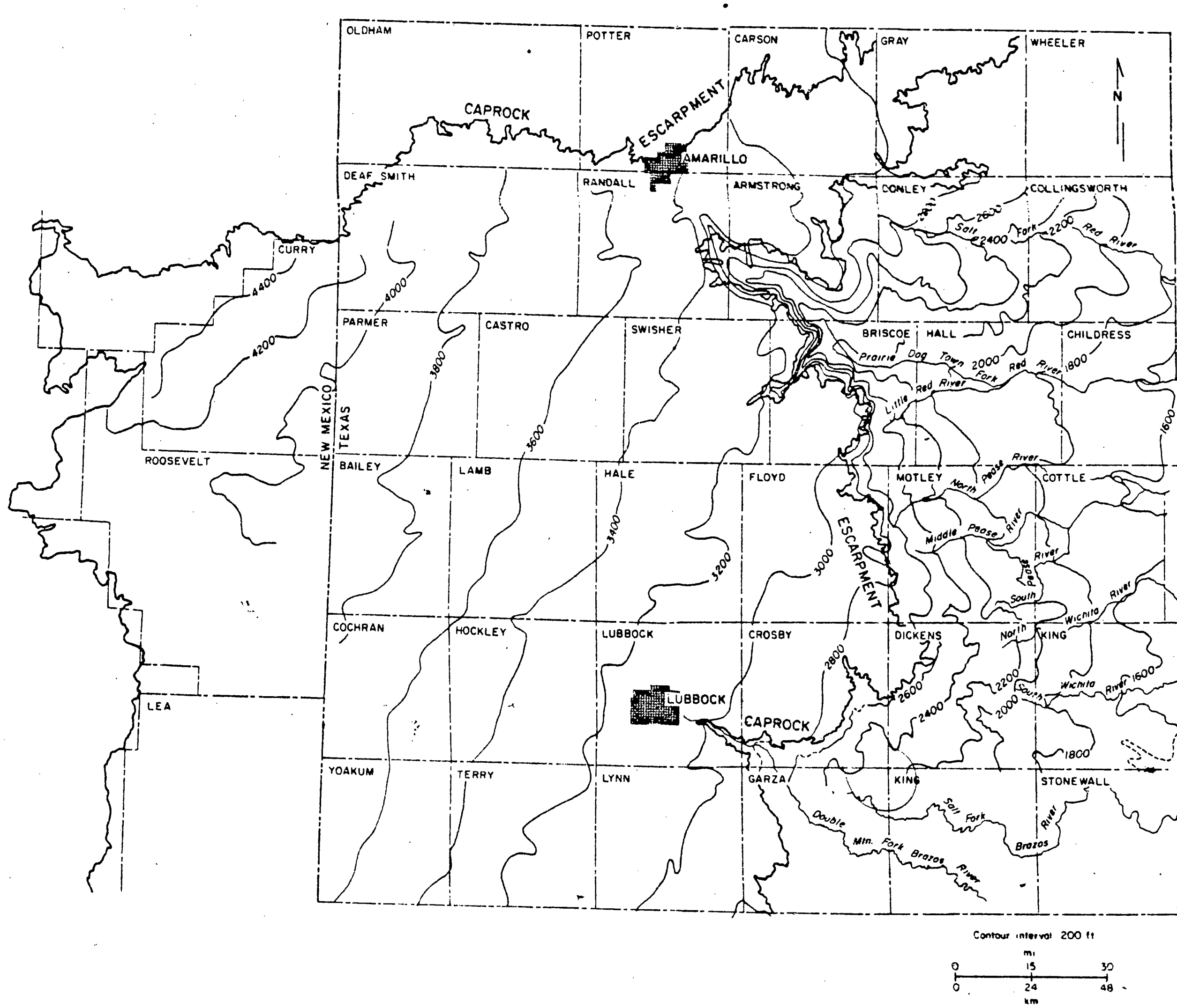


Figure 9



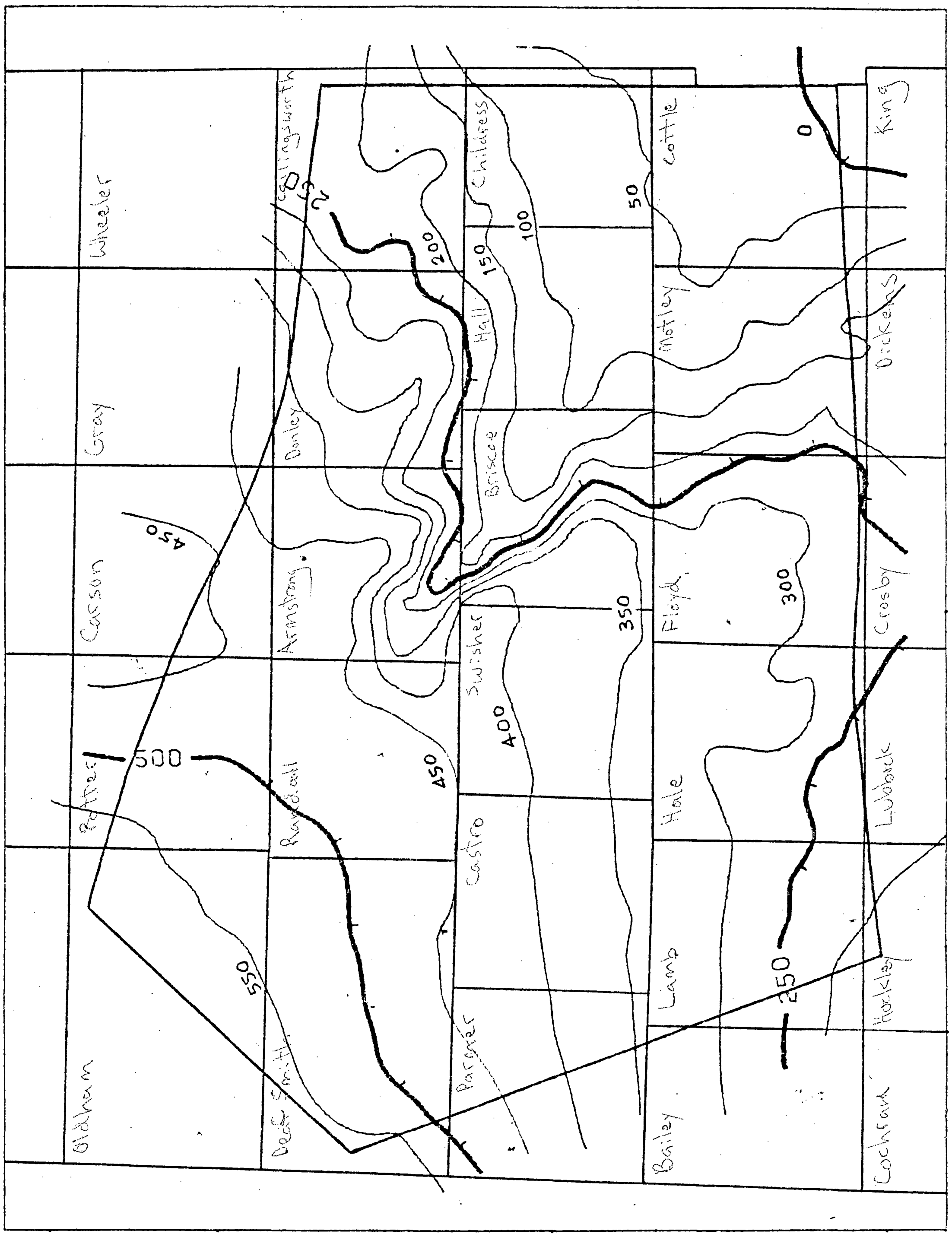
Explanation
North Croton Creek
Dove/Haystack/Croton Creek
Middle Pease River
Jonah/Salt Creek
Interval sampled
(Br/Cl) x 10⁴
Depth (feet)
0
10
20
30
40
50
60
70
80
0
50
100
150
200
250
300
350
400
450
500

See separate file for figures 10a and 10



OLDHAM
POTTER
CARSON
GRAY
WHEELER
N
CAPROCK
ESCARPMENT
AMARILLO
DEAF SMITH
RANDALL
ARMSTRONG
DONLEY
COLLINGSWORTH
CURRY
Salt Fork Red River
4400
4000
4200
PARMER
CASTRO
SWISHER
BRISCOE
HALL
CHILDRESS
Prairie Dog Town Fork Red River
Little Red River
NEW MEXICO
TEXAS
3800
3600
ROOSEVELT
BAILEY
LAMB
HALE
FLOYD
MOTLEY
COTTLE
North Pease River
Middle Pease River
South Pease River
3400
3200
3000
ESCARPMENT
COCHRAN
HOCKLEY
LUBBOCK
CROSBY
DICKENS
KING
North Wichita River
2800
2600
2400
2200
2000
South Wichita River
1600
1800
LUBBOCK
CAPROCK
LEA
YOAKUM
TERRY
LYNN
GARZA
KENT
STONEWALL
Salt Fork Brazos River
Double Mtn. Fork Brazos River
Contour interval 200 ft
mi
0 15 30
0 24 48
km

Figure 12



Oldham
Potter
Carson
Gray
Wheeler
Deaf Smith
Randall
Armstrong
Donley
Collingsworth
Parmer
Castro
Swisher
Briscoe
Hall
Childress
Bailey
Lamb
Hale
Floyd
Motley
Cottle
Cochran
Hockley
Lubbock
Crosby
Dickens
King
550
500
450
400
350
300
250
200
150
100
50
0