

Delineating the Chemical Composition of the Salinity Source for Saline Ground Waters: An Example from East-Central Concordia Parish, Louisiana

by Ronald K. Stoessell^a

Abstract

In the absence of significant water-rock interaction, the chemical composition of a saline brine polluting a ground-water aquifer can be delineated from conservative-mixing relations. An example is the Mississippi River Alluvium Aquifer, within Angelina Plantation in east-central Concordia Parish, Louisiana, which has high ground-water salinities, of unknown origin.

Chloride concentrations are linearly correlated with concentrations of major cations and with bromide and iodide. These relationships are consistent with mixing of fresh water with a saline source of either a single brine or multiple brines of similar composition and with a lack of significant water-rock interactions in the ground water during and after mixing.

The saline source has the following predicted mass ratios for a brine containing 80,000 ppm Cl: Na/Cl, 0.58; Br/Cl, 0.0013; I/Cl, 0.00028; Sr/Cl, 0.0026; K/Cl, 0.0035; Ca/Cl, 0.035; and Mg/Cl, 0.0080. The predicted $^{87}\text{Sr}/^{86}\text{Sr}$ ratio is 0.70805. The mass ratios fall within the range of Tertiary oil-field brines in the Louisiana Gulf Coast. The major reservoir for hydrocarbon production in the area is the Wilcox Formation; however, the "predicted" source brine is unlikely to be a "pure" Wilcox brine from Concordia Parish. Ratios of $^{87}\text{Sr}/^{86}\text{Sr}$ are usually lower and bromide, iodide, and calcium concentrations are always lower in the Wilcox brines than predicted in the saline source.

Introduction

Determining the chemical composition of an unknown brine which pollutes ground water is a priority in an environmental study seeking to identify the polluting brine. This study illustrates the use of conservative mixing to test high-salinity ground water to determine if a single-brine chemistry could produce the observed saline pollution at a field site; and if so, to chemically describe this brine and test whether area oil-field brines, moving up plugged and abandoned oil wells, have the chemical composition to be this saline source. The general applicability of this approach follows from the low surface temperatures and short reaction times of a few years, typical of pollution sites. Water-rock interactions that will destroy conservative-mixing relationships are not likely to be significant under these conditions.

The case study is in Louisiana. High-salinity ground waters, unsuitable for irrigation or drinking, have recently appeared in the Mississippi River Alluvium Aquifer within east-central Concordia Parish in Louisiana (Figure 1). This aquifer underlies the surface of much of northeastern Louisiana, is in hydrologic continuity with the major streams, and is the major source of drinking water (Whitfield, 1975).

The alluvium increases in thickness southward, approaching 200 feet (61 m) in thickness in Concordia Parish and is of Holocene and Pleistocene age (Figure 2), overlying an erosion surface on the Carnahan Bayou Member (Jasper Aquifer) of the Miocene Fleming Formation (Huff and Bonck, 1994). Aquifer recharge is by rainfall which averages over 50 inches annually in northeastern Louisiana and from major streams during high

flood stages. Ground-water flow is generally to the south with discharges into the major streams.

Whitfield (1975) reported that subsurface hydraulic heads in east-central Louisiana indicate Eocene-age waters in the Cockfield Formation have the hydrologic potential to move upward into the Mississippi River Alluvium (Figure 2). Payne

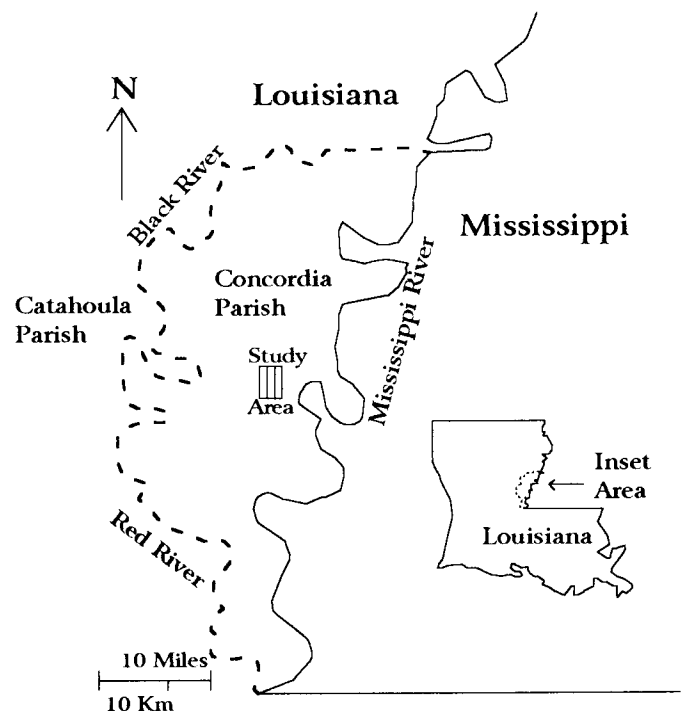


Fig. 1. Location map of the study area in Concordia Parish. The parish is bounded by the Red River on the west and southwest, by the Black River on the northwest and north, and by the Mississippi River on the east. Modified from Huff and Bonck (1993).

^aDepartment of Geology and Geophysics, University of New Orleans, New Orleans, Louisiana 70148.

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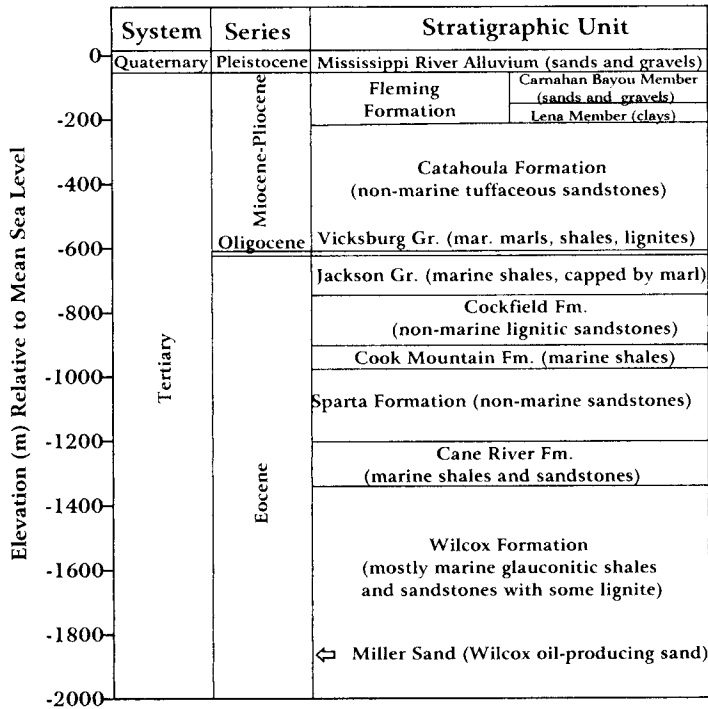


Fig. 2. Stratigraphic column in Angelina Plantation area. Modified from Huff and Bonck (1993), Layne Geosciences, Inc. (1993), Whitfield (1975), Payne (1968), and from Oil Well Resume Reports in the Louisiana Office of Conservation. General lithology is from Chawner (1936).

(1968) came to a similar conclusion for Eocene-age waters in the Sparta Formation. No salt domes penetrate the alluvium and there are no subsurface salt domes in Concordia Parish. Saline ground-water pollution could have resulted from the natural upward movement of subsurface brines following faults into the alluvium, and/or from anthropogenic activities such as surface disposal of oil-field brines in pits and streams, leakage of oil-well casings, and the injection of oil-field brines in brine-injection wells. Upward movement of subsurface fluids in the area may have increased due to overpumping from irrigation which would have increased the hydraulic gradient.

Field Site Description

The ground-water site of this study lies in Angelina Plantation in Concordia Parish (Figure 3a). Ground waters used for irrigation generally have less than 50 mg/l Cl. In the summer of 1982, high chloride concentrations were found in five irrigation wells: IR #3, 554 mg/l Cl; IR #7, 341 mg/l Cl; IR #22, 407 mg/l Cl; IR #24, 916 mg/l Cl; and IR #26, 2350 mg/l Cl, in a 3 square mile area (7.8 km²) in Sections 2, 3, 10, and 11 in T5N, R8E, and Section 34 in T6N, R8E near Bayou Cocodrie and two of its tributaries, Whites and Wyches Bayous (Layne Geosciences, Inc., 1993). Three of the wells (IR #22, IR #24, and IR #26) were new irrigation wells, drilled in May, 1982. The other two wells were drilled in 1978 and had previously produced low-salinity waters.

The high salinities in the irrigation wells have persisted since their first reported occurrence in 1982. The area of high-salinity ground waters in August, 1990, is mapped in Figure 3b, and includes irrigation wells #3, #7, #22, #24, and #26. The area lies in the eastern portion of Angelina Plantation. Maximum salinities were recorded in monitor wells MW #8 and MW #9 in the

southeast corner of Section 3 (Figure 3b) west of Bayou Cocodrie. These wells are north of irrigation well IR #26 which is in the vicinity of the Mississippi Bayou Field and had the maximum salinity of any irrigation well. Hydrology data from the surrounding region west of Bayou Cocodrie indicates ground water in the alluvial aquifer is moving away from the contaminated area, primarily to the west and north but also to the south (Layne Geosciences, Inc., 1993). The direction of ground-water movement east of Bayou Cocodrie is unknown. The movement of ground water to the west and north is against the regional southward flow of ground water and presumably reflects the withdrawal of irrigation water from the alluvium.

Irrigation well #26 is in the center of the Mississippi Bayou Field containing three producing wells and a salt-water disposal well; however, only the discovery well, #179815, had been drilled by the summer of 1982 (Figure 3a). Wells #179815 and #183483 produce from the Miller Sand at about 6,000 ft (1,829 m) in the Eocene Wilcox Formation and were completed in April and November, 1982, respectively. The third producing well, #181880, was completed at 3,345 ft (1,020 m) in the younger Eocene Sparta Formation in August, 1982. The salt-water injection well #183749 was a dry Wilcox test completed in the Sparta Formation at 3,600 ft (1,097 m) in June, 1983, to dispose of brines from the Mississippi Bayou Field. An additional six dry wildcats were drilled from 1983 through 1985 in Sections 10 and 11 of T5N, R8E as field extensions of the Mississippi Bayou Field. Between 1951 and 1979 eight plugged and abandoned Wilcox wildcats

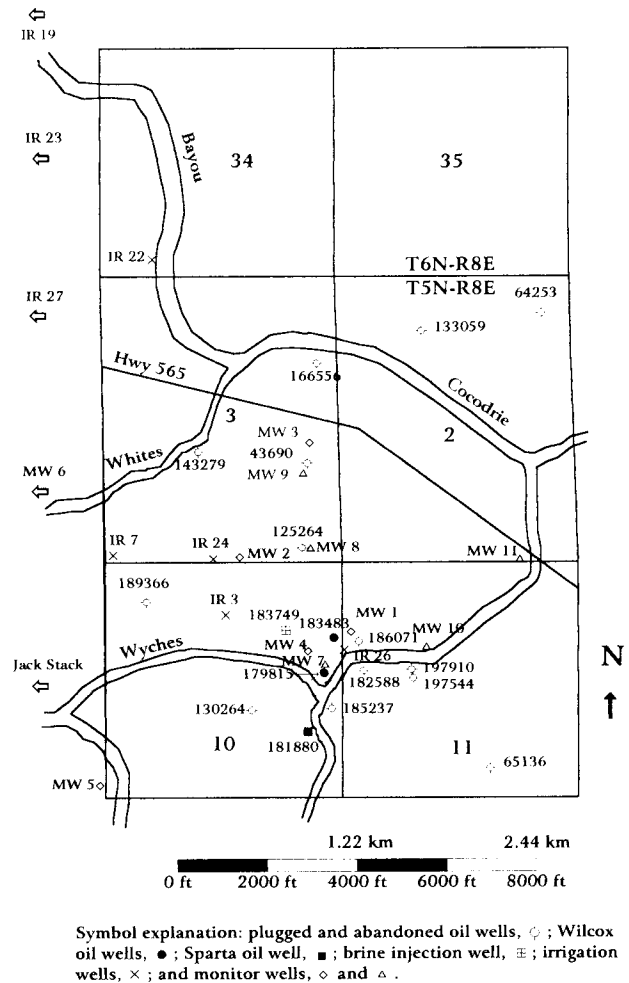


Fig. 3a. Saline ground-water region showing well locations.

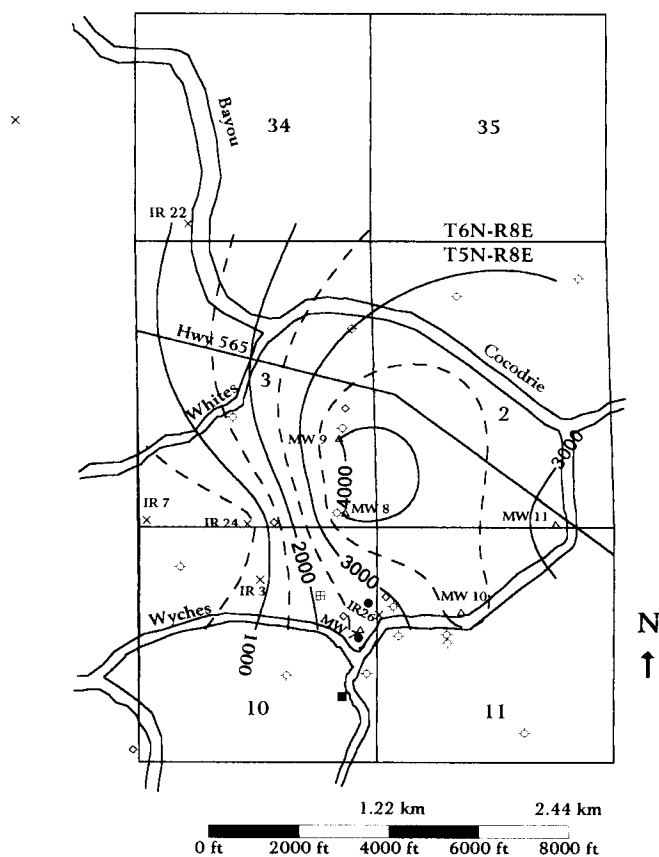


Fig. 3b. Chloride concentrations (mg/l) on 8/18/90 during the irrigation season, using data from Layne Geosciences, Inc. (1993). Symbols are as in Figure 3a. Samples taken only from labeled wells.

had been drilled within the 3 square mile area of present saline ground-water pollution but away from the present Mississippi Bayou Field (Figure 3a). Extending beyond this region are numerous plugged and abandoned Wilcox tests, most drilled between 1950 and 1980. At least one additional salt-water injection well lies within three miles (4.8 km) of the pollution area, the Jack Stack Well #149677 to the west in Section 12, T5N, R7E in the Wilcox-producing South Monterey Field. This well produced oil in 1976 from the Wilcox Formation prior to being used as a Sparta Formation injection well for the South Monterey Field between 1976 and 1992. The author could not determine if only Wilcox brines were injected in this well. (Oil well information is from Oil Well Resume Reports on file in the Louisiana Office of Conservation in Baton Rouge, LA.)

Methods

Application of chemical tracers to link a brine to saline ground water usually involves the assumption of a lack of water-rock interaction, i.e., conservative mixing. If significant water-rock interaction occurs during and after mixing, the uncertainty increases of any chemical linkage between brine and saline ground water, since the fluid compositional changes as a result of reactions are generally unknown.

This study used ground-water concentrations at Angelina Plantation of chloride, bromide, iodide, sodium, potassium, strontium, calcium, and magnesium and the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios from the Mississippi River alluvium and the underlying Carnahan Bayou Member. These data were taken from Whittemore (1986, 1987, 1989, 1993), Layne Geosciences, Inc. (1993), and Huff and

Bonck (1993). Whittemore's data were limited to bromide, iodide, and chloride concentrations. The data from the reports by Whittemore and Layne Geosciences, Inc., are contained in the public records of the Hearing Report for Angelina Plantation Farm (1994). This court case, begun in the early 1980s, sought to establish legal liability for saline contamination of ground water used for irrigation; however, the 1994 court ruling did not establish liability. The compositional data from the Hearing Report, used as part of the data base for this study, have been reproduced in Appendix A. Locations of monitor and irrigation wells from which the samples were taken are shown in Figure 3a. Well nomenclature correlations between Huff and Bonck (1993) and those shown in Figures 3a and 3b are given in Appendix B.

Concentrations in ppm of each ground-water component were plotted versus chloride concentrations for all ground waters from the eastern Angelina Plantation region of high-salinity ground waters (Figure 3b). The use of chloride as the reference component involves the assumption (justified below) that chloride is not affected by water-rock interactions. For $^{87}\text{Sr}/^{86}\text{Sr}$, the ratio was plotted versus the reciprocal of total strontium in ppm. Conservative mixing will produce linear correlations in each of these plots (Stoessell et al., 1989; Faure, 1977).

For each component and for the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio, a least-squares linear regression was made from the ground waters to derive a best-fit ground-water line. Linear correlation coefficients for these ground-water lines ranged from 0.847 to 0.996. The ground-water line for each component was then extended up to brine concentrations (also in ppm) on an additional plot showing available brine data from Concordia Parish and adjacent areas (Collins, 1970; Huff and Bonck, 1993; and bromide, iodide, and chloride data from Whittemore, 1986; 1993). If any of the brines were the saline source for conservative mixing, the line should pass through the region representing their general compositional range.

The plots use ppm, rather than mg/l, because mass, not volume, is conserved during mixing processes. The data conversion involved dividing mg/l by the density (g/cm^3) or specific gravity (assumed equal to the density). Estimated densities were used for brines for which densities were not reported. These were based on linear regression of Concordia Parish Wilcox brine concentrations of chloride versus densities (from Collins, 1970) and unit density (g/cm^3) for distilled water. For consistency sake, mg/l data for the saline ground water were also converted to ppm; however, the differences between ppm and mg/l were not significant for these waters.

Chloride and bromide are often used as chemical tracers in ground-water studies (Whittemore, 1988) because these components are usually considered chemically inert in the absence of halide dissolution or recrystallization (Carpenter, 1978; Stoessell and Carpenter, 1986). The absence of halite minerals in Tertiary and Quaternary rocks in east-central Concordia Parish preclude any interaction with Tertiary oil-field brines.

The aqueous $^{87}\text{Sr}/^{86}\text{Sr}$ ratio, and concentrations of iodide, and the major cations in oil-field brines: sodium, calcium, magnesium, potassium, and strontium are not usually expected to be conserved in a mixing process. Aqueous iodide may be introduced by interactions with organic matter (Collins, 1975), commonly contained in clay-rich sediments. Cations would be expected to undergo cation-exchange reactions as the fluids come into contact with clays. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio is affected by both sulfate-mineral dissolution and by the exchange of stron-

tium on clays, if they have different isotopic ratios. In addition, calcium, and to a lesser extent, magnesium and strontium would be affected by reactions with carbonate minerals. However, the lower alluvium (where the saline pollution exists) is a sand and gravel unit (Whitfield, 1975), lacking carbonates, sulfates, or significant amounts of clays with organic matter.

Saline ground waters from within or just below the alluvium in the vicinity of Angelina Plantation will have had short fluid-rock reaction times (months to years) and low reaction temperatures (earth surface conditions). This follows because the historical records of high salinities indicate mixing took place in this area within the past 15 years. These factors together with the general lack of clays, carbonates, and sulfates in the lower alluvium should minimize the effects of fluid-rock reactions on the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and the concentrations of iodide and the major cations.

Results

Concentration plots of ground-water components plotted versus chloride are shown in Figures 4a–4g for sodium, bromide, iodide, calcium, potassium, magnesium, and strontium, respectively, and for the strontium isotope ratios versus the reciprocal of strontium concentrations in Figure 4h. Figure 4h contains both brine data and ground-water data, the latter being the five points furthest from the y axis. A least-squares linear regression line for the ground-water data, together with the linear equation for the line, the correlation coefficient (r), the coefficient of determination (r^2), and the standard error of estimate (S_{est}) are listed on each plot. The correlation coefficients range from 0.847 to 0.996 in Figure 4. The corresponding coefficients of determination range from 0.718 to 0.993. The good linear correlations of concentrations of chloride with seven other components and of $^{87}\text{Sr}/^{86}\text{Sr}$ with the reciprocal of strontium concentrations can only be explained by fresh water mixing with a single-brine chemistry without significant water-rock interactions. The single-brine chemistry could be from a single brine or multiple brines of similar chemistry.

The least-squares linear regression lines, termed ground-water lines, are extended up to brine concentrations in Figures 5a–5g for the corresponding chemical components shown in Figures 4a–4g, respectively. The standard errors of estimate, listed on Figure 4, are not plotted because they are insignificant on the y scale of the plots in Figure 5. Note that the extension of the $^{87}\text{Sr}/^{86}\text{Sr}$ ground-water line to strontium brine concentrations is shown in Figure 4h. Wilcox brines (Collins, 1970; and Huff and Bonck, 1993) from Concordia Parish and adjacent areas of Catahoula Parish are plotted in Figure 5. In addition, bromide and chloride data from a Wilcox brine, two diluted Wilcox brines, and a Sparta brine from the Mississippi Bayou Field area (Whittemore, 1986), and a brine sample from a 1992 Sparta blowout of the Jack Stack injection well (Whittemore, 1993), located west of Angelina Plantation, are plotted in Figure 5b. These samples together with iodide data from two additional Wilcox samples and one additional Sparta sample from the Mississippi Bayou Field (Whittemore, 1986) are plotted in Figure 5c. Unfortunately, concentrations for the other components used in this study were not reported by Whittemore (1986, 1993).

The ground-water lines pass through the general compositional range of sodium, potassium, magnesium, and strontium in the Wilcox brines in Figures 5a, 5e, 5f, and 5g. However, these brines are depleted in bromide, iodide, and calcium relative to

the ground-water line in Figures 5b, 5c, and 5d, respectively. The bromide depletion is especially evident in Figure 5b in the several Wilcox brines with circled data points. These are the samples having the highest $^{87}\text{Sr}/^{86}\text{Sr}$ ratios from brines (not monitor wells) in Figure 4h and have the predicted $^{87}\text{Sr}/^{86}\text{Sr}$ ratios from the ground-water line. The depletion of bromide and iodide in the Wilcox brines rules them out as the sole source of the ground-water saline pollution at Angelina Plantation. The depletion in calcium could be explained by the ground waters undergoing excessive calcite dissolution and/or cation exchange of sodium for calcium on clays (Cates et al., 1996). However, these reactions should presumably destroy the linear relation between calcium and chloride in Figure 4d.

Samples from the Sparta (Whittemore, 1986) and from the 1992 blowout of the Jack Stack brine injection well (Whittemore, 1993) are not depleted in bromide or iodide relative to the ground-water line in Figures 5b and 5c. The Sparta brine samples are from the area of saline ground water in eastern Angelina Plantation (#181880 on Figure 3a); however, the brine injection well sample was from well #149677 (completed in the Sparta for Wilcox fluid injection) that is located several miles west of this area (Figure 3a). The blowout brine is probably a mixture of Sparta and Wilcox brines; however, that is only conjecture on the author's part. These are the only chemical data available from these samples. Complete oil-field brine compositions from Concordia Parish are only from the Wilcox brines reported by Collins (1970) and Huff and Bonck (1993). Complete chemical data are lacking for Sparta and younger Tertiary-age brines.

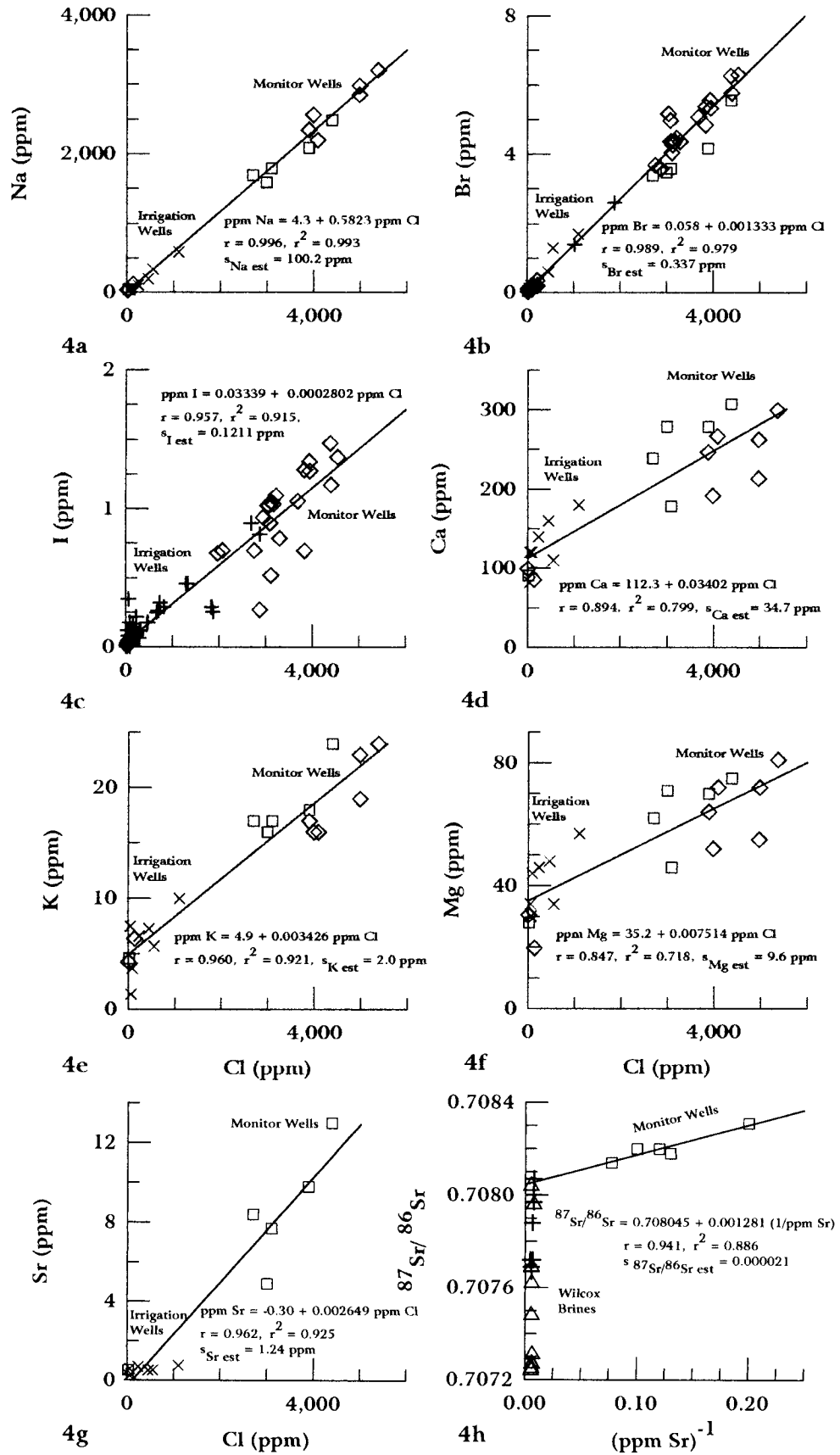
Discussion and Conclusions

The general "saline source" brine chemistry predicted from the ground-water lines in Figure 4h and Figure 5 has a $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.70805 and the following mass ratios (assuming a Cl content of 80,000 ppm): Na/Cl, 0.58; Br/Cl, 0.0013; I/Cl, 0.00028; Sr/Cl, 0.0026; K/Cl, 0.0035; Ca/Cl, 0.035; Mg/Cl, 0.0080. The mass ratios fall within ranges of Tertiary oil-field brines in the Louisiana Gulf Coast that represent sea water concentrated by halite dissolution and modified by albitization of feldspar and other processes (Stoessell and Moore, 1983; Collins, 1970).

The bromide concentrations predicted from the ground-water line are depleted relative to the underlying Mesozoic brines which formed by sea water concentrated by evaporation, modified by dolomitization of limestone, albitization of feldspar, and halite recrystallization (Collins, 1974; Carpenter, 1978; Stoessell and Moore, 1983, 1985).

The linear correlations on Figure 4 imply the saline pollution is from a single-brine source or one or more brines with a limited compositional range. Water-rock interactions have not been significant, following mixing, because this would have destroyed the linear correlations. This lack of water-rock interactions is assumed due to the general lack of clays, organic matter, carbonates, and sulfates in the lower alluvium and the short reaction times and low temperatures of the ground water in the vicinity of eastern Angelina Plantation.

The brine chemistry of the saline source is inconsistent with "pure or unmixed" Wilcox brines which have lower concentrations of bromide, iodide, and calcium, relative to chloride. Sparta brines can have bromide and iodide concentrations consistent with the saline source; however, confirming data for other



Symbol explanation. Monitor wells: \square , Huff and Bonck (1993); \diamond , Layne Geosciences, Inc., (1993) and Whittemore (1986, 1987, 1989, and 1993). Irrigation wells: \times , Huff and Bonck (1993); $+$, Whittemore (1986, 1987, 1988, and 1993), in Figures 4a-4g. Wilcox brines in Figure 4h are from Huff and Bonck (1993): \triangle , from Concordia Parish and $+$, from Catahoula Parish. \square in Figure 4h are ground waters from monitor wells from Huff and Bonck (1993).

Fig. 4. Best-fit lines of Angelina ground water computed from ground-water data shown in Figures 4a-4h.

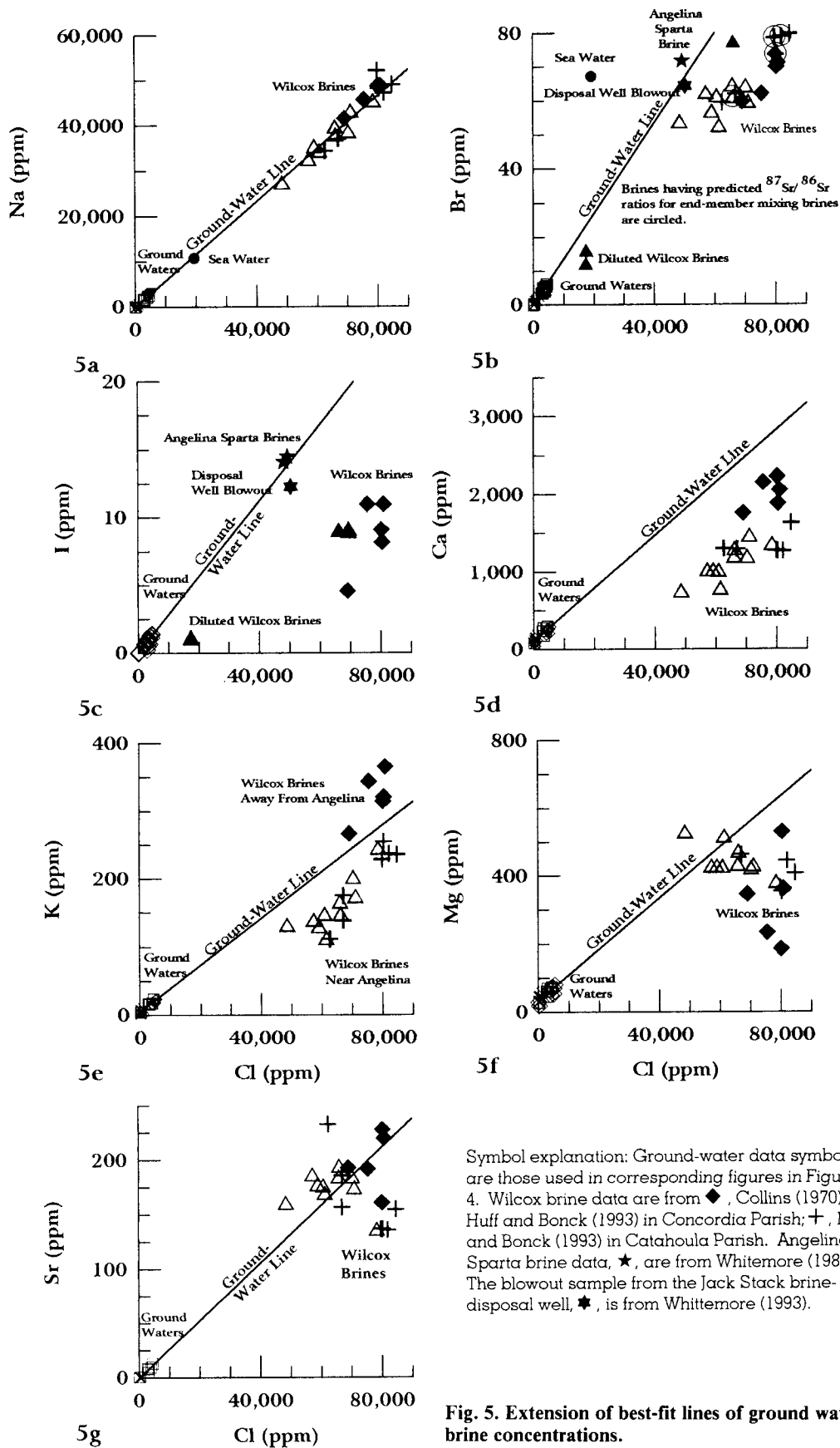


Fig. 5. Extension of best-fit lines of ground water to brine concentrations.

components are lacking for these fluids. Complete chemical data are needed for both Sparta brines and the younger Tertiary brines (e.g., Cockfield brines) to see if they are compatible with the predicted brine-source chemistry.

The low temperatures and short reaction times typical of many saline pollution sites will limit fluid-rock interactions. Under these conditions, the procedure used in this case study has general applicability for determining source-brine chemistry.

Appendix A. Concentrations from Whittemore and from Layne Geosciences, Inc., Reported in Public Records of Angelina Court Case, and Used in This Study After Conversion to ppm (Table Numbers Refer to Those Used in the Referenced Data Sources)

Bromide, Chloride, and Iodide Concentrations from Whittemore (1986)

Table 2. Monitor (Test) Wells in August, 1983

Monitor wells	depth ft	Cl mg/l	Br mg/l	I mg/l
1	120	97		0.064
	160	2,950		0.940
2	120	95	0.1	0.064
	138	1,960		0.680
3	120	106	0.2	0.060
	160	2,070		0.700
4	120 [@]	213	0.28	0.099
	144 [@]	3,055	5.1	1.030
5	120	44		0.019
	144	81		0.031

[@]Average of two samples, one refrigerated immediately after collection.

Table 4. Irrigation Wells in 1985

Irrig. wells	Depth ft	April 10-11, 1985		August 26, 1985	
		Cl mg/l	I mg/l	Cl mg/l	I mg/l
3	97	26	0.025	43	0.033
3	117			163	0.080
3	122	296	0.118	223	0.096
3	127	690	0.260	660	0.250
3	131	50	0.025	1,290	0.460
4	97	20	0.015		
4	102			42	0.024
4	112	28	0.018		
4	122	23	0.020		
4	127			56	0.031
4	132	70	0.038	56	0.032
7	82			91	0.029
7	87	86	0.005	77	0.016
7	92			74	0.026
7	102	91	0.027	66	0.027
7	117			86	0.028
7	122	134	0.048	131	0.054
22	78	98	0.044	88	0.043
22	108	218	0.090	183	0.078
22	113	460	0.180	311	0.120
22	118	810	0.290	450	0.180
22	122			95	0.060
24	98	79	0.180	42	0.120
24	113	146	0.170	55	0.080
24	118	216	0.220	117	0.090
24	123	725	0.320	109	0.120
26	77	10	0.0048	223	0.080
26	92	9	0.005		
26	97			104	0.053
26	102			155	0.065
26	107	276	0.067	176	0.075
26	112	800	0.123	472	0.180
26	117	1,840	0.290	1,320	0.460
26	122	2,880	0.820	2,690	0.900

Other samples in Table 4, not listed above, lacked iodide concentrations, so could not be used in this study. Chloride concentrations are reported from the Kansas Geological Survey if more than one analysis was reported.

Table 5. Irrigation Well# on May 17, 1985

Irrig. well	Depth ft	Cl mg/l	I mg/l	Br mg/l
26	9 from bottom	1,870	0.480	2.62 [@]

[#]Data were reported from samples from the same well following pumping. The sample reported above from Table 5, for use within this study, was taken after the longest pumping time.

[@]The bromide concentration was not reported in Table 5 in Whittemore (1986) but in Table 13 in Whittemore (1989).

Table 6. Brines# in 1983

Sample	Formation	Date	Cl mg/l	I mg/l	Br mg/l
Brine	Wilcox	9/83	71,200	9.8	83
Brine pit	diluted Wilcox	7/83	17,600	1.23	12
Brine well pit	diluted Wilcox	7/83	17,700	1.17	16
Brine 10	Sparta	10/83	51,900	15.3	76

[#]These brines are from the three producing wells in the Mississippi Bayou Field in the Angelina Plantation area. From the text discussion by Whittemore, brine 10 appears to be from VUB Madison BP #1 which was the only well producing from the Sparta Formation in the field. The other brine sample with its two diluted samples is from either the VUA Madison BP #1 or the Madison BP #2 which were the Wilcox producers. Other brine samples, reported in Table 6, lacked bromide data and were not included in the chloride-iodide data because there was no text discussion on where these brines came from or what they represented.

Table 7. Brines# on June 18, 1984

Well	Formation	Cl mg/l	I mg/l
VUA Madison BP #1	Wilcox	74,900	9.7
VUB Madison BP #1	Sparta	51,800	15.3
Madison BP #2	Wilcox	74,900	9.9

[#]Other reported brine data were from treaters or mixtures in storage tanks and were not included in the chloride-iodide data.

Bromide, Chloride, and Iodide Concentrations from Whittemore (1987)

Table 8. Irrigation Wells on December 17, 1986

Irrig. wells	Depth ft	Cl mg/l	I mg/l
3	20	8.5	0.023
3	50	8.3	0.022
3	75	18	0.027
3	100	102	0.065
3	120	923	0.337
3	135-140	802	0.302
7	20	91	0.031
7	50	91	0.029
7	75	79	0.022
7	100	43	0.027
7	120	215	0.092
24	20	61	0.365
24	50	42	0.278
24	75	42	0.040
24	100	140	0.076
24	126	654	0.228
26	20	2.6	0.0089
26	50	2.2	0.0053
26	75	1.6	0.0042
26	100	186	0.085
26	120	2,980	0.985
26	126	2,720	0.900

Table 12. Irrigation Wells on October 31, 1988 (Depths Were Not Reported)

Irrigation wells	Cl mg/l	Br mg/l	I mg/l
3	10.7		0.0166
7	90	0.13	0.047
24	56	0.06	0.346
26	12.7	0.10	0.023

Bromide, Chloride, and Iodide Concentrations from Whittemore (1993)

Table 1. Monitor (Test) Wells Collected on August 18, 1990, and from a Blowout of the Jack Stack Salt-Water Disposal Well on May 6, 1992 (Sample Depths for Monitor Wells Were Not Reported)

Monitor wells	Cl mg/l	Br mg/l	I mg/l
6	21.7	0.11	0.017
7	2,760	3.7	0.70
8	4,410	5.8	1.18
9	3,690	5.1	1.06
10	3,840	4.9	0.70
11	2,080	3.6	0.27
Jack Stack	53,100	68.3	13.0

Bromide, Chloride, and Iodide Concentrations from Whittemore (1989)

Table 11. Monitor (Test) Wells[@] in 1988

Monitor wells	Depth ft	Cl mg/l	Br mg/l	I mg/l
6	110-130 [#]	18.6	0.03	0.0132
	190-210 [#]	144	0.18	0.061
7	300-320	3,840	5.4	1.290
7B	200-220	3,170	4.4	1.040
8	210-230	4,390	6.3	1.480
9	185-205	3,130	4.3	1.050
10	210-230	3,940	5.6	1.350
11	172-192	3,220	4.5	1.100

[@]Well #6 was sampled on December 2, 1988; remaining wells were sampled on October 31, 1988.

[#]Concentrations are the average of two reported samples.

Table 2. Pumped Monitor (Test) Wells[@] Collected from August 14-19, 1993

Monitor wells	Cl mg/l	Br mg/l	I mg/l
6	20.3	0.04	0.016
7	3,119	4.07	0.52
8	4,550	6.34	1.38
9	3,096	4.30	0.90
10	3,957	5.37	1.28
11	3,300	4.39	0.79

[@]The reported compositions are from samples taken after one hour of pumping. Other reported data lacked bromide concentrations and were for samples following shorter time periods of pumping, and were not included in the chloride-iodide data used in this study.

Monitor (Test) Well Data from Layne-Geosciences, Inc. (1993)

Monitor wells	Depth feet	Date sampled	Cl mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
6	190-210	12/03/88	133	122	6.4	85.6	19.8
7	300-320	10/25/88	5,000	3,000	22.85	215	55
7B	200-220	10/25/88	3,900	2,360	17.13	248	64
8	210-230	10/20/88	5,400	3,230	24.43	302	81
9	185-205	10/19/88	4,100	2,210	15.86	268	72
10	210-230	10/21/88	5,000	2,870	18.96	265	72
11	172-192	11/30/88	4,000	2,580	16.28	193	52

Appendix B

Huff and Bonck (1993) reported their data using a different well nomenclature than those shown on Figures 3a and 3b which correspond to the well nomenclature of Layne Geosciences, Inc., 1993. Well correlations are as follows: IR #3, Co-115; IR #19, Co-122; IR #22, Co-119; IR #23, Co-120; IR #26, Co-178; IR #27, Co-114; MW #6, Co-205; MW #7, Co-204; MW #8, Co-202; MW #9, Co-201; MW #10, Co-203; and MW #11, Co-200. The Co-43 sample of Huff and Bonck (1993) was not used because its depth was nearly 700 feet (213 m which is far below the alluvium), the sample was reported taken in 1967 which is 21 years prior to the other samples), and, most important, the fluid chemistry is abnormal, a nearly pure sodium chloride fluid.

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