RECONNAISSANCE INVESTIGATION OF EVAPORITES AND BRINES OF THE EASTERN PROVINCE, KINGDOM OF SAUDI ARABIA

by

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ABSTRACT

In the Eastern Province of the Kingdom of Saudi Arabia from south of Al Hasa oasis (about lat 25° N., long 50° E.) north to near the southern border of the neutral zone between Saudi Arabia and Kuwait (about lat 28° N., long 48° E.), sabkhah-associated brines form either by solar evaporation of near-surface ground water or by dissolution of previously precipitated saline minerals in the subsurface. Most sabkhah-associated brines have evolved from fresher ground water by the process of solar evaporation. One of the major controls of sulfate, calcium, and bicarbonate concentrations in brines is equilibrium reactions of these ions with authigenic minerals in sabkhah sediments. Although equilibrium reactions also provide some control of concentrations of magnesium, potassium, sodium, and chlorine, the concentrations of these elements in brines are controlled primarily by the degree to which the solutions have evaporated.

Salt for industrial use in the Eastern Province is currently supplied from the Ra's al Qurayyah and Aba al Hamam bedded salt deposits, both of which are naturally exposed. At Jayb Uwayyid, a bedded salt deposit approximately 3.5 m below the sabkhah surface is not currently exploited.

Except on a small scale, brines in the Eastern Province are not being utilized, either directly or for the production of salt. The Jayb Uwayyid deposit has some potential for industrial utilization of brine and salt, and further exploration for this type of salt deposit is probably warranted.

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INTRODUCTION

Brines and evaporites are raw materials used in manufacturing many industrial chemicals including chlorine gas used in producing some plastics, ethylene dibromide used in gasoline antiknock preparations, potassium used in fertilizer, sodium carbonate and boric acid used in manufacturing glass, and sodium sulfate used in manufacturing paper. Brines and evaporites worth billions of dollars are produced worldwide each year.

Many currently exploited evaporite and (or) brine deposits formed by solar evaporation. The economic importance of ancient evaporite deposits is one of the factors that stimulated the search for modern analogs to these deposits. The coast of the United Arab Emirates (Trucial States), which borders Saudi Arabia on the east, has become a classic area for the study of active evaporitic processes. Studies by Kinsman (1965, 1969), Butler (1969, 1973), Patterson (1972, unpublished data), Bush (1973), and by many others have helped define the processes that are active in sabkhah environments. These studies have led to a reevaluation of many ancient evaporite deposits to determine if the deposits contain sedimentary features characteristic of modern sabkhahs.

This report provides a preliminary evaluation of the economic potential of evaporites and brines in the Eastern Province of the Kingdom of Saudi Arabia (fig. 1). More than 160 brine samples collected intermittently from October 13, 1978, to January 30, 1981, from sample localities south of Al Hasa oasis north to near the southern border of the neutral zone between Kuwait and Saudi Arabia (fig. 1, pl. 1) were analyzed.

The author thanks A. Baraja for chemical analyses of the samples and K. J. Curry for his help in supplying field and laboratory equipment. The author gratefully acknowledges D. J. Faulkender for supplying longitude and latitude information for several sample localities and Faulkender, G. I. Selner, and M. DeMatteo for help with sample collecting. The author also thanks R. J. Patterson (1972, unpublished data) for the loan of a copy of his thesis.

The work on which this report is based was performed in accordance with a cooperative agreement between the U. S. Geological Survey (USGS) and the Saudi Arabian Ministry of Petroleum and Mineral Resources.

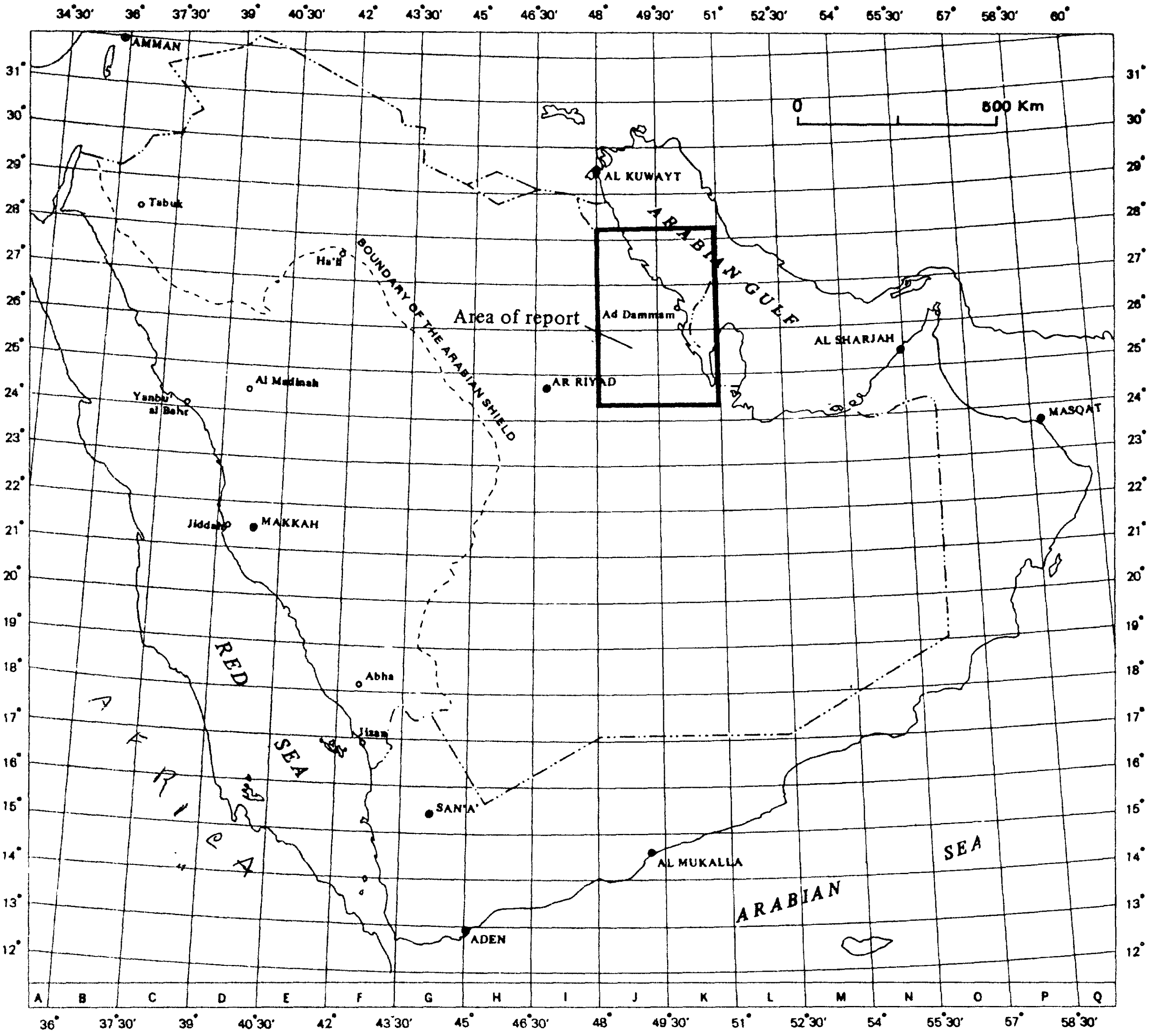

Figure 1.–Index map of Saudi Arabia showing location of area of report.

SAMPLING AND ANALYTICAL METHODS

Water samples were collected from holes dug to ground water, from springs and wells, and from the Arabian Gulf (pl. 1). The water samples were analyzed in the DGMR (Directorate General of Mineral Resources)-USGS chemical laboratory. Most water samples are brines collected from holes dug to the water table. A typical hole from which a water sample was collected was about 50 cm in diameter at the sabkhah surface and tapered to about 30 cm in diameter at the water table.

Samples were collected in 500-ml polyethylene bottles that had been cleaned with distilled water and dried. The bottles were rinsed with sample prior to filling and sealed after filling. Samples that contained visible quantities of suspended sediment were filtered in the laboratory. The pH was measured in the laboratory with a pH meter and combination glass pH electrode. Bicarbonate was measured in the laboratory by titration of the sample to a pH of 4.5 with dilute sulfuric acid. Calcium, magnesium, sodium, and potassium concentrations were determined by atomic absorption techniques with an atomic absorption spectrophotometer. Chloride concentration and fluoride activity were measured with Orion electrodes. Concentration of silica (molybdate blue method) and sulfate (turbidimetric method)(Tabatabai, 1974) were determined with a spectrophotometer. Dilute conductivity (Rossum, 1949) was measured with a conductivity meter. Water-sample density was measured with a chain gravitometer. Charge balance and agreement between measured and calculated specific conductance (Rossum, 1949) are within ± 14 percent. In 148 of 164 analyzed water samples, charge balance and agreement between measured and calculated specific conductance are within ± 5 percent. Results of the analyses are presented in table 1.

The average relative standard deviations of the analytes are presented in table 2. These values are calculated by methods suggested by Garrett (1969) and described in Rose and others (1979) and are based on the results of the analyses of 10 duplicate water samples. The term analyte is used to indicate the element or physical property being determined. Because the average relative standard deviations given in table 2 are based on only 10 duplicate water samples, they must be regarded as approximations. The average relative standard deviation, also known as the coefficient of variation (Rose and others, 1979), provides an estimate of the precision of an analytical method. The precision of the data presented in table 1 is sufficient to indicate whether a water sample contains an anomalous quantity of an individual ion in solution and to delineate general geochemical trends in the data. However, the data are probably neither precise nor accurate enough to use in thermodynamic calculations.

Table 1.--*Chemical analysis and location of water samples from the Eastern Province, Kingdom of Saudi Arabia*
[Results for Ca, Mg, Na, K, Cl, SO_4, and HCO_3 are in meq/l; SiO_2, Li, and F in mg/l; calculated conductivity in micromhos; density in gm/cm^3; lat and long in decimal degrees]

DMMR NUMBER	Ca	Mg	Na	K	Cl	SO4	HCO3	SiO2	CAL. COND.	pH	Li	F	DENSITY	LAT	LONG
120300	24.0	1200.0	4261.0	140.7	4795.0	487.0	2.9	3.6	653.0	7.0	0.0	.6	1.202	25.414	49.886
120301	35.5	47.5	168.0	8.2	204.0	62.5	2.6	44.2	34.0	8.5	0.0	1.9	1.012	25.845	49.786
120302	7.5	3.9	17.4	1.0	19.7	7.0	3.9	29.5	3.5	8.5	0.0	.8	1.001	26.118	49.541
120303	32.5	533.0	4739.0	173.9	5204.0	233.0	.7	3.8	673.0	7.5	0.0	.2	1.198	26.236	49.548
120304	39.5	410.0	2826.0	61.4	3103.0	335.0	5.3	6.7	428.0	7.6	0.0	.9	1.135	26.349	49.737
120305	213.0	426.0	5000.0	74.2	5360.0	34.8	.3	4.8	693.0	6.6	0.0	.4	1.198	26.293	49.917
120306	70.0	274.0	3000.0	69.1	3047.0	176.0	.7	6.6	428.0	7.0	0.0	.9	1.129	26.282	49.632
120307	83.0	557.0	4217.0	86.9	4654.0	95.8	.5	4.3	631.0	7.0	0.0	.5	1.182	26.683	49.865
120308	82.0	1049.0	4739.0	158.6	6037.0	69.2	.5	3.0	733.0	6.7	0.0	1.6	1.208	26.736	49.854
120309	283.0	860.0	4349.0	140.7	5642.0	26.0	.4	10.9	680.0	6.1	0.0	.9	1.201	26.759	49.846
120310	13.3	1426.0	4435.0	166.2	5642.0	566.0	3.0	1.9	747.0	7.0	0.0	1.2	1.225	25.414	49.886
120311	45.5	209.0	1435.0	33.3	1721.0	37.5	1.7	6.3	216.0	7.2	0.0	1.3	1.070	26.158	50.139
120312	106.0	360.0	3609.0	63.9	4231.0	99.7	.9	6.5	525.0	6.8	0.0	1.0	1.153	28.047	48.617
120313	335.0	134.0	1096.0	38.4	1467.0	37.9	.6	29.1	202.0	7.1	0.0	3.4	1.067	28.178	48.434
120314	21.0	152.0	752.0	17.1	818.0	82.3	2.4	.2	110.0	7.9	0.0	1.9	1.035	27.174	49.578
120315	15.6	606.0	1626.0	44.0	2228.0	36.4	2.6	5.2	286.0	7.5	0.0	.9	1.086	27.035	48.408
120316	9.2	6.9	17.0	.6	21.2	10.4	1.4	17.0	4.1	7.1	0.0	1.7	1.001	26.484	48.551
120500	64.5	73.8	222.0	5.4	270.0	123.0	1.9	28.1	47.7	7.0	.6	2.4	1.018	25.914	49.901
120501	57.0	46.7	196.0	10.5	226.0	72.9	3.2	54.0	36.3	7.2	.3	2.0	1.012	25.915	49.946
120503	21.0	18.0	61.7	1.8	81.8	18.5	.6	21.8	12.2	7.2	.2	1.0	1.004	25.996	50.054
120504	280.0	1230.0	3830.0	156.0	5640.0	26.5	3.5	10.1	713.0	5.9	.5	1.0	1.206	26.747	49.856
120506	53.0	246.0	1087.0	41.9	1280.0	326.0	3.5	11.0	205.0	7.6	1.6	5.0	1.061	25.559	50.212
120507	36.0	25.4	62.6	3.3	77.3	50.0	3.5	64.0	15.2	7.4	.2	1.7	1.005	25.346	49.784
120508	179.0	796.0	4300.0	125.0	5590.0	41.3	.4	4.9	687.0	6.7	.7	.3	1.198	26.230	49.956
120509	26.0	20.5	100.0	2.0	113.0	32.5	.8	25.0	17.4	7.8	.2	1.7	1.001	26.456	49.736
120510	53.5	508.0	2960.0	53.7	3390.0	255.0	3.3	5.1	468.0	7.0	1.8	.4	1.137	26.501	49.725
120511	102.0	549.0	3440.0	207.0	4800.0	82.3	.7	7.0	570.0	6.9	1.7	.9	1.160	26.563	49.735
120512	650.0	1570.0	3520.0	128.0	5810.0	9.4	.3	2.8	738.0	6.4	2.4	.9	1.212	26.618	49.811
120513	146.0	861.0	4350.0	69.3	5360.0	59.6	.5	5.3	647.0	6.7	.5	.7	1.194	26.172	50.091
120514	68.0	434.0	2000.0	59.1	2400.0	170.0	1.0	5.5	320.0	7.1	.5	1.7	1.103	27.176	49.536
120515	109.0	654.0	4170.0	289.0	4650.0	80.0	.9	5.3	613.0	6.8	.4	1.0	1.182	27.099	49.481
120516	240.0	1360.0	3700.0	40.2	4940.0	34.8	.5	17.8	673.0	6.4	.5	.7	1.195	27.066	49.302

Table 1.--*Chemical analysis and location of water samples from the Eastern Province, Kingdom of Saudi Arabia*-Continued

DMMR NUMBER	Ca	Mg	Na	K	Cl	SO4	HCO3	SiO2	CAL. COND.	pH	Li	F	DENSITY	LAT	LONG
120517	96.5	467.0	1610.0	35.0	2190.0	159.0	1.1	5.5	287.0	7.2	1.1	1.8	1.080	27.782	48.723
120518	260.0	1470.0	3570.0	62.9	5220.0	34.8	.7	4.7	663.0	6.6	.9	2.2	1.200	27.390	48.454
120519	75.5	287.0	3260.0	26.9	3530.0	167.0	.6	5.8	470.0	6.9	1.2	.8	1.143	27.075	49.175
120520	132.0	336.0	1570.0	15.1	2090.0	103.0	1.1	8.8	279.0	7.0	1.1	3.3	1.075	27.279	48.870
120521	132.0	245.0	1300.0	27.1	1690.0	91.7	.8	14.9	238.0	7.0	.8	3.1	1.072	27.206	48.838
120522	150.0	426.0	1130.0	25.1	1690.0	99.6	1.0	12.8	226.0	7.2	.8	3.7	1.062	27.259	48.607
120523	40.0	172.0	3740.0	55.5	3890.0	325.0	1.2	5.1	520.0	7.4	.5	.1	1.147	27.154	48.584
120524	140.0	680.0	1040.0	48.9	2120.0	34.4	2.4	10.2	270.0	7.7	1.1	1.6	1.079	27.014	48.402
120525	425.0	2520.0	2300.0	161.0	5920.0	16.5	2.0	4.9	793.0	6.4	2.0	4.3	1.216	27.027	48.415
120529	125.0	762.0	4170.0	102.0	5080.0	57.9	.7	1.9	673.0	6.6	1.5	.7	1.183	26.188	50.118
120530	110.0	730.0	3040.0	81.8	4090.0	99.4	.9	4.1	550.0	6.7	7.0	.4	1.147	26.586	49.882
120531	80.0	189.0	522.0	14.1	719.0	116.0	2.0	24.3	102.0	7.6	1.8	3.4	1.017	26.889	49.647
120532	105.0	137.0	1390.0	11.0	1480.0	98.8	1.9	12.4	202.0	7.0	.4	1.3	1.054	27.078	49.347
120533	80.0	631.0	4560.0	89.5	5080.0	92.3	.8	1.3	700.0	6.6	1.2	1.3	1.185	26.121	50.127
120534	100.0	844.0	4090.0	113.0	5360.0	84.2	.7	13.8	686.0	6.0	1.1	.8	1.176	27.071	49.303
120535	86.5	779.0	4610.0	97.2	5640.0	75.2	.7	1.2	753.0	6.7	1.4	1.3	1.187	26.768	49.781
120536	120.0	623.0	3870.0	79.3	4940.0	73.2	.8	6.0	660.0	7.0	.7	2.6	1.166	27.079	49.309
120537	130.0	648.0	4220.0	84.4	5220.0	74.0	.6	1.7	666.0	6.7	1.1	1.9	1.187	27.107	49.335
120538	33.5	172.0	826.0	19.0	903.0	87.3	2.4	.5	137.0	8.0	.3	2.0	1.029	27.130	49.361
120539	115.0	139.0	1300.0	11.3	1550.0	88.5	1.8	10.5	210.0	7.4	.4	1.3	1.051	27.078	49.347
120540	135.0	557.0	4350.0	84.4	5590.0	98.8	.3	2.1	700.0	6.6	.6	1.1	1.178	27.098	49.313
120541	115.0	557.0	4130.0	64.0	4800.0	83.0	2.0	8.2	653.0	7.0	.6	1.7	1.178	27.086	49.316
120542	75.0	598.0	3570.0	72.0	4090.0	133.0	1.0	3.1	540.0	6.9	.8	1.4	1.161	27.129	49.360
120543	115.0	459.0	4090.0	77.0	5080.0	72.0	.6	2.4	667.0	6.4	.8	.5	1.171	26.826	49.748
120544	60.0	713.0	3780.0	87.0	5220.0	127.0	1.3	2.4	645.0	6.9	1.0	2.2	1.178	27.121	49.347
120545	100.0	1160.0	4170.0	141.0	5920.0	54.8	.6	2.1	773.0	6.2	2.0	.5	1.204	26.729	49.783
120546	165.0	779.0	3960.0	87.0	5360.0	56.7	1.3	3.7	652.0	6.3	.8	6.0	1.168	27.084	49.338
120547	125.0	1050.0	4220.0	76.7	5920.0	54.8	1.2	1.7	762.0	6.6	2.4	1.9	1.191	27.256	48.607
120548	110.0	762.0	4220.0	105.0	5250.0	66.8	.6	1.0	685.0	6.5	1.1	1.2	1.178	27.114	49.341
120549	110.0	598.0	3910.0	79.0	4800.0	75.0	.9	5.1	625.0	6.6	.6	2.7	1.181	27.079	49.309
120550	110.0	607.0	3480.0	67.0	4650.0	84.4	.9	2.2	575.0	6.6	1.5	1.5	1.155	27.088	49.331
120551	170.0	500.0	4130.0	74.2	4850.0	71.3	.5	3.7	612.0	6.6	.6	1.3	1.161	27.093	49.322
120552	145.0	516.0	4040.0	59.0	5220.0	51.0	.7	2.2	656.0	6.1	1.1	.8	1.182	26.846	49.714
120553	70.0	467.0	2520.0	48.6	3240.0	172.0	1.4	3.4	412.0	7.1	.8	2.0	1.110	27.128	49.353
120554	105.0	369.0	3130.0	46.0	3890.0	88.0	.9	3.6	494.0	6.7	1.9	1.5	1.128	27.108	49.296

Table 1.--*Chemical analysis and location of water samples from the Eastern Province, Kingdom of Saudi Arabia*-Continued

NWMR NUMBER	Ca	Mg	Na	K	Cl	SO4	HCO3	SiO2	CAL. COND.	pH	Li	F	DENSITY	LAT	LONG
120555	115.0	664.0	4040.0	97.0	5360.0	65.8	.4	1.5	687.0	6.5	1.0	.7	1.192	27.100	49.328
120556	205.0	525.0	3130.0	53.0	3950.0	47.0	.7	4.7	540.0	6.4	1.5	.8	1.137	26.744	48.647
120557	160.0	525.0	4170.0	59.0	5190.0	45.4	.5	3.0	640.0	6.1	1.6	1.2	1.145	26.777	48.668
120558	170.0	533.0	4350.0	97.0	5080.0	57.0	.3	1.5	680.0	6.7	.9	.3	1.172	27.103	49.305
120559	31.0	131.0	521.0	14.8	748.0	83.0	.3	.3	106.0	7.7	.2	1.6	1.033	27.414	49.221
120560	90.0	467.0	2391.0	61.4	2820.0	127.0	.8	6.5	393.0	7.0	3.2	.2	1.104	26.335	49.832
120561	10.5	8.2	195.0	1.5	217.0	4.4	3.8	26.4	29.2	7.8	0.0	.8	1.009	26.114	49.542
120562	51.0	303.0	1700.0	79.0	2060.0	275.0	1.3	12.3	294.0	7.3	3.3	.6	1.099	26.128	49.543
120563	52.0	295.0	609.0	22.3	917.0	124.0	2.2	24.6	129.0	7.3	1.1	1.5	1.038	25.941	50.020
120564	52.0	271.0	1740.0	58.8	1980.0	244.0	1.3	11.2	283.0	7.0	3.3	1.3	1.082	26.220	49.516
120565	110.0	779.0	4000.0	105.0	5710.0	60.0	.4	2.6	693.0	6.8	6.3	1.3	1.189	26.328	49.843
120566	25.0	78.0	478.0	29.4	508.0	81.7	1.9	19.5	74.2	7.6	1.1	.3	1.019	25.997	49.523
120567	130.0	713.0	3650.0	113.0	4800.0	66.5	.4	3.3	661.0	6.7	1.7	1.0	1.183	26.203	50.076
120568	90.0	434.0	2830.0	51.0	3530.0	117.0	.6	6.7	469.0	6.7	6.6	.3	1.124	26.407	49.993
120569	120.0	566.0	4300.0	100.0	4510.0	163.0	.5	2.9	619.0	6.8	3.7	.6	1.173	26.267	50.011
120570	120.0	803.0	3830.0	125.0	5190.0	68.5	.4	4.1	673.0	6.6	1.2	1.1	1.179	26.166	50.094
120571	105.0	205.0	2610.0	79.0	2910.0	302.0	1.3	9.5	380.0	6.9	4.1	.6	1.104	26.043	49.595
120572	90.0	434.0	3260.0	56.3	3530.0	119.0	.6	4.9	452.0	6.8	4.2	.3	1.119	26.326	49.992
120573	135.0	197.0	1780.0	118.0	1980.0	114.0	.6	12.2	289.0	7.0	2.6	1.4	1.075	26.261	49.891
120574	50.0	221.0	1040.0	59.0	1370.0	179.0	1.9	15.1	183.0	7.3	2.3	.8	1.048	26.235	49.539
120575	55.0	779.0	4440.0	110.0	5760.0	143.0	.7	2.1	707.0	6.9	4.0	1.2	1.196	26.144	49.921
120576	115.0	557.0	4220.0	102.0	5130.0	67.0	.5	2.9	660.0	6.8	1.0	1.5	1.196	26.216	49.991
120577	55.0	467.0	2870.0	141.0	2820.0	456.0	1.2	6.4	444.0	7.1	5.1	.2	1.123	26.096	49.567
120578	75.5	443.0	4350.0	123.0	5220.0	83.3	.4	1.8	633.0	6.8	4.4	.5	1.197	26.291	49.919
120579	80.0	533.0	3520.0	92.0	4230.0	140.0	.7	3.0	520.0	7.0	4.2	.4	1.156	26.155	49.914
120580	85.0	320.0	1830.0	38.4	2120.0	151.0	1.2	7.6	279.0	7.2	2.2	1.1	1.095	26.300	49.828
120581	96.5	762.0	3960.0	117.0	5360.0	77.5	.4	2.3	679.0	6.7	3.3	.9	1.188	26.223	49.960
120582	52.0	434.0	4170.0	74.0	5020.0	125.0	.7	2.7	650.0	6.9	1.2	.1	1.188	26.225	50.022
120583	55.0	410.0	2000.0	48.6	2230.0	162.0	1.1	6.7	370.0	7.3	2.8	.1	1.109	26.354	49.822
120584	65.0	393.0	2040.0	61.4	2740.0	302.0	1.0	6.2	327.0	7.1	.7	1.5	1.086	26.174	50.058
120585	70.0	434.0	3300.0	56.3	3950.0	165.0	1.1	4.7	500.0	7.0	1.4	1.1	1.152	25.743	50.129
120586	105.0	566.0	4520.0	87.0	5360.0	84.2	.8	2.5	667.0	6.9	.9	1.3	1.191	26.154	49.975
120587	100.0	230.0	2260.0	61.4	2820.0	41.7	.9	4.1	360.0	7.4	.6	1.0	1.086	26.221	49.968
120588	65.0	820.0	4570.0	110.0	5920.0	119.0	.7	2.1	747.0	6.9	4.1	1.4	1.206	26.144	49.921
120589	70.0	279.0	1780.0	61.4	2050.0	234.0	1.2	11.3	300.0	7.1	3.2	1.3	1.087	26.220	49.516

Table 1.--*Chemical analysis and location of water samples from the Eastern Province, Kingdom of Saudi Arabia*-Continued

DMMR NUMBER	Ca	Mg	Na	K	Cl	SO4	HCO3	SiO2	CAL. COND.	pH	Li	F	DENSITY	LAT	LONG
120590	75.0	426.0	3350.0	59.0	3950.0	149.0	.8	4.4	510.0	7.0	1.4	1.2	1.157	25.743	50.129
120591	135.0	566.0	4390.0	69.0	5640.0	50.2	.2	1.9	689.0	6.8	4.8	.4	1.197	26.306	49.870
144000	49.0	164.0	1350.0	15.1	1460.0	158.0	1.5	16.7	212.0	7.3	1.5	2.2	1.078	27.030	49.361
144001	38.5	41.8	174.0	5.6	188.0	52.1	2.0	37.5	32.0	7.7	.6	4.2	1.014	26.289	49.922
144002	57.5	54.0	422.0	2.4	536.0	37.7	1.6	28.7	65.6	7.6	.1	.9	1.021	26.260	49.887
144003	405.0	721.0	3910.0	102.0	5360.0	9.8	1.0	3.8	661.0	6.1	5.4	.3	1.227	26.275	49.887
144004	97.5	303.0	1220.0	23.0	1680.0	119.0	1.0	10.6	221.0	7.2	2.0	1.2	1.076	26.339	49.829
144005	66.0	434.0	2830.0	76.7	3290.0	7.5	.7	6.7	432.0	7.1	3.9	.1	1.140	26.358	49.822
144006	68.0	590.0	3520.0	84.4	4030.0	114.0	.5	6.3	550.0	6.8	3.5	.2	1.168	26.367	49.820
144007	187.0	475.0	4480.0	61.4	5360.0	34.0	.3	4.2	673.0	6.6	3.6	.3	1.201	26.274	49.899
144008	460.0	967.0	3910.0	94.6	5640.0	19.4	.3	3.7	707.0	6.2	4.7	.5	1.207	26.276	49.904
144009	930.0	1480.0	2610.0	169.0	5590.0	4.9	.3	2.4	733.0	5.8	7.6	1.2	1.217	26.284	49.901
144010	120.0	795.0	4260.0	113.0	5420.0	74.0	.4	3.8	687.0	6.7	4.7	.7	1.207	26.294	49.905
144011	530.0	740.0	3610.0	113.0	5360.0	15.7	.3	3.5	647.0	6.2	6.4	.7	1.203	26.278	49.874
144012	255.0	473.0	3830.0	64.0	5080.0	31.0	.3	3.2	665.0	6.2	3.8	.2	1.201	26.286	49.880
144013	275.0	779.0	4350.0	58.8	5590.0	37.7	.3	4.4	680.0	6.1	3.9	.2	1.203	26.294	49.877
144014	123.0	271.0	1260.0	10.2	1470.0	82.9	1.3	43.7	192.0	6.9	1.6	2.5	1.065	26.321	49.718
144015	62.0	689.0	3130.0	74.2	3970.0	192.0	1.9	10.8	525.0	6.6	2.6	1.7	1.163	26.970	49.548
144016	145.0	811.0	3910.0	105.0	4650.0	68.0	1.3	9.3	585.0	6.5	1.9	1.7	1.184	26.987	49.543
144017	153.0	762.0	3350.0	79.3	4230.0	63.8	1.4	11.7	510.0	6.8	1.2	2.4	1.172	27.016	49.528
144018	72.5	631.0	3830.0	79.3	4800.0	113.0	.7	2.3	590.0	6.4	1.0	.9	1.181	27.105	49.459
144019	82.0	369.0	3440.0	58.8	3720.0	127.0	.8	5.0	515.0	6.6	3.7	.3	1.158	26.787	49.578
144020	168.0	443.0	3090.0	40.9	3890.0	62.5	.5	4.9	480.0	6.8	1.7	.9	1.150	26.770	49.575
144021	180.0	549.0	4440.0	56.3	5500.0	29.6	.3	4.1	673.0	6.5	2.3	1.0	1.203	26.744	49.571
144022	49.1	312.0	3220.0	33.3	3750.0	101.0	.9	7.0	473.0	6.7	3.2	.7	1.145	26.717	49.576
144023	52.0	123.0	1090.0	14.1	1100.0	199.0	.9	9.9	157.0	7.5	1.3	.8	1.056	26.690	49.580
144024	52.0	82.0	413.0	5.1	437.0	110.0	.4	25.9	65.3	7.1	.6	4.6	1.025	26.671	49.585
144025	78.0	500.0	4350.0	48.6	5080.0	55.8	.4	4.7	627.0	6.4	4.6	1.1	1.191	26.308	49.866
144026	580.0	1310.0	3440.0	118.0	5590.0	4.8	.2	3.2	727.0	6.1	5.3	1.4	1.207	26.301	49.897
144027	100.0	98.4	187.0	4.1	188.0	104.0	1.6	34.4	36.0	7.3	.6	5.2	1.015	26.305	49.907
144028	94.0	344.0	3870.0	33.0	4230.0	81.3	.6	6.3	575.0	6.6	4.9	.3	1.169	26.266	49.881
144029	77.0	98.0	504.0	5.4	617.0	80.0	.9	41.5	87.0	7.9	1.3	1.5	1.031	26.274	49.876
144030	78.0	87.0	509.0	5.9	654.0	72.0	1.1	41.6	84.2	6.9	1.0	2.2	1.030	26.290	49.870
144031	70.5	87.7	739.0	8.4	814.0	60.4	1.4	55.0	103.0	6.9	1.1	2.1	1.035	26.302	49.863
144032	93.5	738.0	4350.0	107.0	5330.0	71.7	.5	3.9	700.0	6.5	5.8	.9	1.202	26.332	49.836

Table 1.--*Chemical analysis and location of water samples from the Eastern Province, Kingdom of Saudi Arabia*-Continued

DMMR NUMBER	Ca	Mg	Na	K	Cl	SO4	HCO3	SiO2	CAL. COND.	pH	Li	F	DENSITY	LAT	LONG
144033	103.0	639.0	3650.0	41.0	4770.0	55.0	.4	6.8	585.0	6.3	4.7	1.2	1.177	26.325	49.845
144034	158.0	336.0	2090.0	24.0	2650.0	116.0	.8	17.6	330.0	6.9	3.3	1.5	1.105	26.317	49.856
144035	88.5	574.0	2830.0	48.6	3390.0	100.0	.9	9.7	450.0	6.3	6.4	1.2	1.141	26.322	49.829
144036	71.0	213.0	1700.0	18.0	1830.0	135.0	1.0	12.9	244.0	6.9	1.5	1.5	1.082	27.082	49.185
144037	74.5	557.0	4350.0	92.0	5220.0	105.0	.5	2.0	640.0	6.9	3.9	.5	1.195	27.083	49.176
144038	78.5	738.0	4440.0	138.0	5360.0	80.0	.7	2.1	709.0	6.7	4.5	.9	1.208	27.079	49.180
144039	191.0	762.0	3780.0	7.5	4650.0	46.7	.3	4.0	620.0	6.5	1.2	1.1	1.181	27.067	49.559
144040	55.0	139.0	513.0	12.0	677.0	82.5	2.9	0.0	93.0	7.1	.2	1.6	1.032	27.048	49.633
144041	84.0	205.0	1700.0	18.7	1860.0	150.0	1.2	17.1	255.0	7.2	1.6	1.9	1.083	27.081	49.206
144042	48.0	197.0	1440.0	15.9	1590.0	177.0	1.0	19.1	214.0	6.8	1.6	2.4	1.072	27.030	49.361
144043	98.0	836.0	4260.0	97.2	5360.0	81.0	.8	3.7	673.0	6.5	4.6	1.1	1.200	26.294	49.905
144044	128.0	270.0	1090.0	17.9	1480.0	100.0	1.7	38.1	187.0	6.9	1.7	2.6	1.065	26.321	49.718
144051	20.0	1967.0	4391.0	335.0	4807.0	2313.0	1.8	1.5	872.0	6.5	3.3	.8	1.267	25.815	49.720
144052	80.0	1246.0	4000.0	243.0	5924.0	108.0	1.0	1.9	741.0	6.2	.7	.7	1.213	25.932	50.077
144053	50.0	156.0	1517.0	26.6	1509.0	215.0	.9	7.7	227.0	6.9	1.0	.8	1.075	26.675	49.584
144054	55.0	139.0	1430.0	24.0	1444.0	227.0	.8	8.1	204.0	7.0	.9	1.0	1.069	26.681	49.583
144055	55.0	164.0	1608.0	21.7	1470.0	252.0	.9	7.5	231.0	6.8	.9	1.1	1.075	26.693	49.581
144056	75.0	221.0	2087.0	33.0	2539.0	150.0	1.1	7.9	333.0	6.8	1.2	.6	1.104	26.700	49.578
144057	100.0	328.0	3565.0	62.9	4231.0	49.0	.5	5.8	540.0	6.4	1.1	.3	1.159	26.714	49.575
144058	65.0	221.0	2087.0	36.8	2482.0	176.0	1.1	7.1	333.0	6.7	1.0	.7	1.106	26.710	49.567
144059	160.0	319.0	4826.0	50.9	5219.0	31.7	.2	3.0	627.0	6.2	.9	.3	1.194	26.529	49.801
144060	535.0	1057.0	3348.0	128.0	5219.0	21.7	.3	2.8	660.0	6.0	1.8	.5	1.197	26.560	49.747
144061	550.0	1057.0	3565.0	92.0	5506.0	15.0	.2	3.0	677.0	5.9	1.4	.1	1.206	26.551	49.730
144062	110.0	492.0	3868.0	87.0	4671.0	62.5	.4	4.7	613.0	6.3	1.5	.4	1.177	26.513	49.728
144063	380.0	1495.0	3348.0	158.0	5360.0	15.8	.2	3.2	713.0	6.4	2.5	.1	1.206	26.534	49.725
144064	4.2	787.0	4086.0	123.0	5360.0	16.7	.3	3.2	713.0	6.0	.4	1.4	1.207	26.558	49.755
144069	100.0	491.0	3869.0	92.0	4654.0	48.0	.3	4.9	590.0	6.4	1.1	.1	1.177	26.513	49.728

Table 2.--Approximate average relative standard deviations of chemical analyses in table 1

[Statistics based on the following pairs of duplicate samples: 120300, 120310; 120564, 120589; 120575, 120588; 120585, 120590; 120532, 120539; 120536, 120549; 144042, 144000; 144043, 144010; 144044, 144014; 144062, 144069. Duplicate samples used for these calculations were collected at the sample site in separate bottles and submitted for analysis in random sequence. Results for Ca, Mg, Na, K, Cl, SO_4, and HCO_3 are in meq/l; SiO_2, Li, and F in mg/l; calculated conductivity in micromhos; density in gm/cm^3]

Analyte	Average value	Average standard deviation	Average relative standard deviation (in percent)
Calcium (Ca)	82.5	8.29	10.0
Magnesium (Mg)	532	53.1	10.0
Sodium (Na)	2990	70.0	2.3
Potassium (K)	69.6	7.1	10.2
Chloride (Cl)	3650	199	5.5
Sulfate (SO_4)	161	20.2	12.5
Bicarbonate (HCO_3)	1.23	.19	15.6
Silica (SiO_2)	10.5	1.49	14.2
Calculated conductivity	476	25.4	5.3
pH	6.89	.18	2.6
Lithium (Li)	1.89	.09	5.2
Fluoride (F)	1.45	.19	12.9
Density	1.14	.007	0.6

Although the pH values given in table 1 are relatively precise, they are not necessarily accurate because accurate determination of pH is particularly difficult in waters having high ionic strength (Bates, 1973). The difficulties described by Bates in determining pH in solutions of high ionic strength also apply to some extent to other electrochemical analytical methods. Because both fluoride activity and bicarbonate concentration were determined by electrochemical methods, those results are also of questionable accuracy.

Water analyses can be checked with the dilute conductance method (Rossum, 1949). This method compares the specific conductance of a water sample diluted by distilled water to a conductivity between 90 and 120 micromhos with the specific conductance calculated by summation of the increments of conductance contributed by each determined ion in the sample. Dilution of a water sample to a conductivity of between 90 and 120 micromhos tends to break into their component ions the labile (unstable) complexes and ion pairs that often form in brines. The calculated conductivity values given in table 1 were not directly measured but instead are based on the conductivity of water samples diluted by distilled water to a conductance between 90 and 120 micromhos. The calculated conductivity can be found by solving the following formula:

$$C = ((M1 + M2)/M2)*D/1{,}000,$$

where C is the calculated conductivity (in millimhos), M1 is the volume (in ml) of distilled water used to dilute the sample, M2 is the volume (in ml) of sample, and D is the specific conductance (in micromhos) of the diluted sample.

GEOLOGY OF SABKHAHS

Many of the first studies of sabkhahs (also spelled sabkhas) were conducted on the coast of the United Arab Emirates (Kinsman, 1969). Generally, the descriptions of these sabkhahs and the physical processes active in them also apply to sabkhahs in Saudi Arabia (Skipwith, 1971; Johnson and others, 1978). Kinsman (1969) described sabkhahs in the United Arab Emirates and defined two basic types, continental sabkhahs and coastal sabkhahs, both of which are present within 100 km of the Arabian Gulf coast of Saudi Arabia. The sabkhahs in the United Arab Emirates (Patterson, 1972, unpublished data), like those in Saudi Arabia, are characterized by a shallow water table and an open hydrologic system. Most of the sabkhah surfaces are approximately in deflational equilibrium (Kinsman, 1969). The height to which the capillary fringe of the ground water extends above the water table determines the base level to which deflation is effective in removing sediment. Below the capillary fringe, sediments are too moist to be easily removed by deflation.

Based on studies of Br/Cl and Br/K ratios, Patterson and Kinsman (1977) found that a large percentage of the water in the hydrologic systems of both coastal and continental sabkhahs in the United Arab Emirates is derived from continental rather than marine sources. In Saudi Arabia, most of the water underlying both coastal and continental sabkhah surfaces is probably also of continental origin.

The two largest oases in the Eastern Province are Al Qatif and Al Hasa (pl. 1). Both oases have abundant near-surface waters. At Al Qatif, hand-dug wells penetrate an Eocene dolomitic limestone of the Dammam Formation and karst springs are common. At Al Hasa, springs discharge from a Neogene marly limestone of the Hofuf Formation (Job, 1978). Dincer and others (1974) believe that all coastal-belt aquifers in the Eastern Province are connected and that water from rocks of the Umm ar Radhuma Formation of Paleocene and early Eocene age penetrates overlying aquifers. Based on both water chemistry and static water levels in the various aquifers, Job (1978) suggested that in the area of both Al Hasa and Al Qatif oases, all Tertiary aquifers are hydrologically connected by faults and (or) joints and discharge water from rocks of the Umm ar Radhuma Formation. He further suggested that in the area of Al Hasa oasis, water from rocks of the Umm ar Radhuma Formation rises along joints to beds of Neogene age without any significant loss of pressure.

Studies by Dincer and others (1974) and Job (1978) suggest the following origin of sabkhahs in the Eastern Province: Water from the Umm ar Radhuma Formation rising along faults and (or) joints locally produces a water table in the overlying unconsolidated eolian sediments high enough for a sabkhah surface to form in equilibrium with deflational processes. Fault or joint control of sabkhah formation would also explain the observation that the long axes of many of the sabkhah surfaces in the eastern coastal belt north of lat 27° N. appear to be parallel or subparallel (pl. 1). In this area, the long axes of the sabkhah surfaces trend slightly northeast of north and do not appear to be related to the present coastline. Both Red Sea transform faults (D. Stoeser, 1981, oral commun.) and the long axis of the Ghawar anticline also trend approximately the same direction, but the similarity of trends may be fortuitous.

EVAPORITES

In modern sabkhahs on the Arabian Peninsula, authigenic minerals such as aragonite, high-magnesium calcite, gypsum, anhydrite, celestite, halite, dolomite, magnesite, and huntite have been found (Kinsman, 1969; Bush, 1973). Unlike the authigenic minerals found in ancient evaporite deposits, most authigenic minerals in modern sabkhahs on the Arabian Peninsula either have not yet been found in sufficient quantity to justify commercial exploitation, or they contain contaminating elements that discourage their industrial utilization. Halite is the only authigenic evaporite mineral currently exploited in Saudi Arabia. Whereas the halite reported on the coast of the United Arab Emirates is described as forming a crust on the sabkhah surface (Kinsman, 1969), three known bedded salt (halite) deposits, each at least 4 m thick, are associated with sabkhahs in Saudi Arabia. Probably none of these salt deposits extends horizontally more than 10 km in any direction. The thicknesses of these deposits indicate that they did not form at or below a sabkhah surface. They probably formed at a sediment-solution or salt-solution interface.

The Arabian American Oil Company (1955a) described a bedded salt deposit 6 km north of Umm as Sahik (pl. 1) that was approximately 1.2 m thick and a surface crust of halite located about 10 km westerly of Umm as Sahik (pl. 1) that ranged in thickness from a few centimeters to about 16 cm. Both these deposits are located on Sabkhah ar Riyas. The Arabian American Oil Company (1955b) also discovered a bedded halite deposit while it was drilling seismic survey holes across Sabkhah Jayb Uwayyid (Sabkha Jab Awaiyid). The halite was in a continuous bed that ranged from about 30 cm to about 4 m in thickness and was about 5 km long and 1.8 km wide. The top of the bed was approximately 3 to 4.5 m below the sabkhah surface. The Arabian American Oil Company (1955b) estimated the deposit to be at least 11 million cubic meters in size and to contain in excess of 24 million metric tons of salt. Salt in this deposit is not being exploited.

Salt for use in Saudi Arabia is being produced 10 km south of Ra's al Qurayyah and at the Sabkhah Aba al Hamam (pl. 1). Both deposits are naturally exposed at sabkhah surfaces. The salt produced is used by Basic Chemical Industries (R. Ashford, oral commun., 1981) for the generation of chlorine gas and caustic soda and by Arabian American Oil Company at some of its oil refining and production facilities. Although salt has been produced at Aba al Hamam for several years, there is no indication that the deposit at Ra's al Qurayyah produced salt prior to 1979. In both deposits, the method of salt production and the appearance of the salt is similar. The salt forms layers that range from about 1.3 cm to more than 8 cm in thickness, layers 3 cm thick being common. These salt layers are separated by layers less than 2 mm thick that are composed of silt- and clay-size particles and anhydrite. Some anhydrite nodules as much as 5 cm in diameter are also found. Salt is mined with an excavator that is capable of recovering salt located at least 4 m below the sabkhah surface. Because the water table is within 15 cm of the sabkhah surface, a brine-filled pit remains where the salt was removed.

At Ra's al Qurayyah, salt is collected in the excavator bucket and sloshed two or three times in the brine to help remove the interlayered silt, clay, and anhydrite. After a salt and mud mixture that usually covers the salt surface is scraped away, the washed salt is piled beside the excavated pit. At Aba al Hamam, salt is excavated without being sloshed in the brine and is piled beside the brine-filled pit. To partially clean the salt at Aba al Hamam, brine is pumped over the salt pile from the adjacent brine-filled pit. At both deposits, the partially cleaned salt is transported by truck to the site where it is utilized.

At Ra's al Qurayyah, at least 7 km^2 of bedded salt is located either at or within 10 cm of the sabkhah surface and the salt is at least 4 m thick in the area where it is mined. At Aba al Hamam, at least 0.25 km^2 of bedded salt is exposed and the salt is at least 4 m thick in the area where it is mined. The Ra's al Qurayyah deposit probably contains at least 64 million metric tons of salt, and the Aba al Hammam deposit at least 3 million metric tons.

BRINES

Chemistry

More than 160 water samples were collected in the Eastern Province from continental and coastal sabkhahs, wells, springs, sumps, and the Arabian Gulf (pl. 1). Water samples from sabkhahs were collected from hand-dug holes that reached ground water. The water table was mostly at depths less than 90 cm below the sabkhah surface. More than 40 water samples, the largest number of samples from an individual sabkhah, were collected from the Jayb Uwayyid sabkhah.

Sabkhah-associated brines in the eastern coastal belt form either by solar evaporation of the ground water below a sabkhah surface or by partial dissolution of preexisting saline minerals. Most sabkhah-associated brines are probably the product of solar evaporation.

On and near the east coast of Saudi Arabia, the water table is less than 100 cm below the sabkhah surface in most places. Because of the relatively shallow depth to the water table, water in the upper part of the capillary fringe can evaporate and a brine can form within the sabkhah sediments. However, the evaporation rate of ground water through the upper part of a sabkhah is much less than the evaporation rate of water exposed at the ground surface (Patterson, 1972, unpublished data).

In the Eastern Province, ions that constitute a significant percentage of the total solute weight include sodium, potassium, calcium, magnesium, chloride, and sulfate and are referred to as major ions. The method by which a brine has evolved, whether by solar evaporation or by dissolution of saline minerals, may not greatly affect the resulting major-ion chemistry of the brine. If a brine forms by solar evaporation, chemical equilibrium in the brine is maintained by the precipitation of authigenic minerals when their solubility in the brine is exceeded. If a water contacts a mineral with which the water is undersaturated, the mineral will dissolve until the contacting water is saturated with that mineral. The brines produced by either of these processes are in equilibrium with minerals that commonly are found in sabkhah environments, and the major-ion chemistry of brines produced by either process may be similar, without regard for of the mechanism by which they evolved.

Calculated conductivity is a useful quantity for monitoring the behavior of individual elements as they are concentrated in solution by evaporation. Whereas individual elements tend to precipitate in the crystal lattice of minerals whose solubility is exceeded during evaporation of the enclosing solution, the calculated conductivity, like the total dissolved solids, increases in proportion to the amount of water removed from the solution by evaporation. To calculate the amount of total dissolved solids in solution requires determination of the concentration of most of the major ions present in the sample. To determine the calculated conductivity requires only that the specific conductance of the diluted sample be measured. For these reasons, calculated conductivity is the preferred quantity to use for estimating the total amount of major ions in solution and for monitoring the behavior of individual elements as they are concentrated in solution by evaporation.

Another method of monitoring the evaporative evolution of seawater is by measuring the density of the evolving brine. Density data for seawater have been determined by Usiglio (in Clarke, 1924). The density of water from the Mediterranean Sea is 1.026 gm/cm^3; halite will begin to precipitate from seawater after it has evaporated to a density of 1.214 gm/cm^3. Although the source of water for most brines that evolved in the eastern coastal belt is continental ground water rather than seawater, the relative proportions of the major ions are close to those in seawater (Clarke, 1924). The main difference between the relative proportions of major ions in seawater (fig. 2) and an average brine sample collected from the Eastern Province (fig. 3) is that the relative amount of chloride is about 5 weight percent less in seawater than in average ground water and the relative amount of sulfate is about 5 weight percent greater.

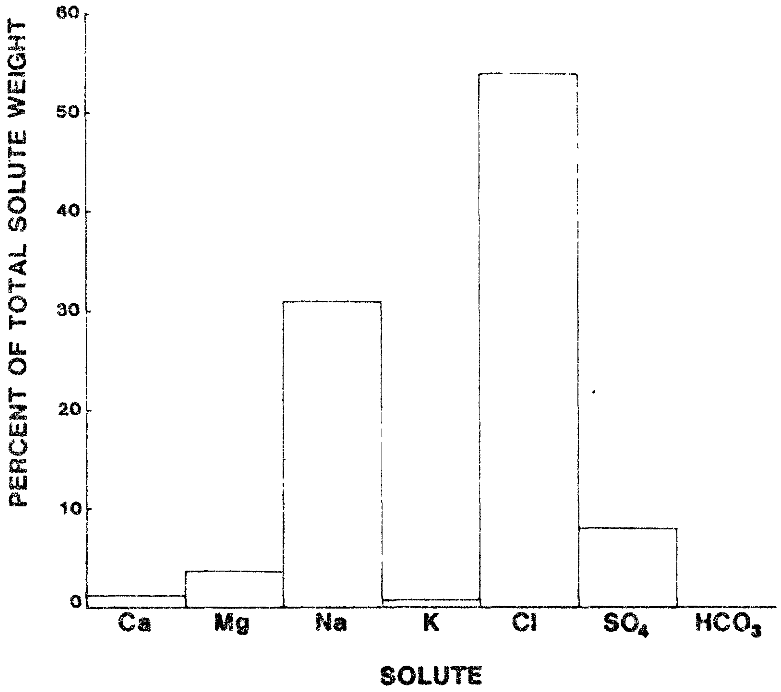

Figure 2.--Histogram showing relative proportions of major ions in water from the Mediterranean Sea (Clarke, 1924).

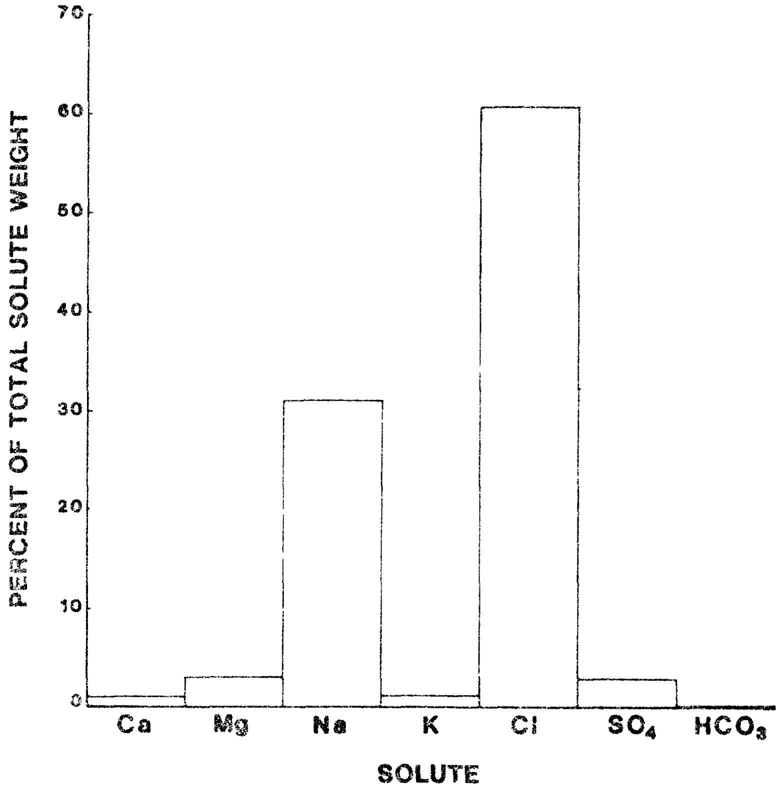

Figure 3.--Histogram showing relative proportions of major ions in an average water sample collected for this study.

Whereas this difference may slightly affect the density at which halite precipitates from the coastal brines, the density determined by Usiglio (in Clarke, 1924) for the precipitation of halite from seawater is essentially valid for most coastal brine samples.

Most samples had not evaporated to the extent that they had become saturated with halite. Only 5 brine samples had a density greater than 1.214 gm/cm^3, but 26 brine samples had a density greater than 1.20 gm/cm^3 (fig. 4). Sample 144051 had the highest density (1.267 gm/cm^3); it was collected from the brine pit in the Aba al Hamam salt deposit, where the brine is exposed to the atmosphere. The other 4 samples having densities greater than 1.214 gm/cm^3 were either associated with salt that had precipitated on the sabkhah surface or were collected from holes dug to ground water above the buried salt deposit at Jayb Uwayyid.

Gypsum is a common mineral in sabkhah sediments in the Eastern Province, and most if not all ground water associated with sabkhahs in this area is probably saturated with gypsum regardless of ground-water density (Johnson and others, 1978). Gypsum saturation of sabkhah-associated brines was also noted on the United Arab Emirates coast by Patterson (1972, unpublished data). As equal molar amounts of calcium and sulfate are removed from solution upon evaporation of gypsum-saturated water, a Ca/SO_4 molar ratio greater than one will increase and a ratio less than one will decrease upon evaporation of the water, unless the ratio is modified by other processes during the evolution of the water. The less conductive samples, those which have probably evaporated the least, have Ca/SO_4 ratios whose logs tend to cluster around an equal molar ratio line (fig. 5). The more conductive samples have ratios whose logs tend to diverge significantly from the line. Although other processes, such as dolomitization and sulfate reduction, can affect calcium and sulfate concentrations in the waters of this area, the most important chemical control of these ions is probably gypsum precipitation (fig. 5).

The process that primarily controls the concentrations of both potassium and magnesium in solution is probably evaporation without the accompanying precipitation of minerals that incorporate these elements in the lattices. As the calculated conductivity increases, there is a general increase in the concentrations of both potassium and magnesium (figs. 6, 7). Dolomitization may also affect the concentration of magnesium in sabkhah-related brines, but it is not the major process controlling magnesium concentration (fig. 7). Butler (1969) extensively discussed the dolomitization process for a coastal sabkhah in the United Arab Emirates.

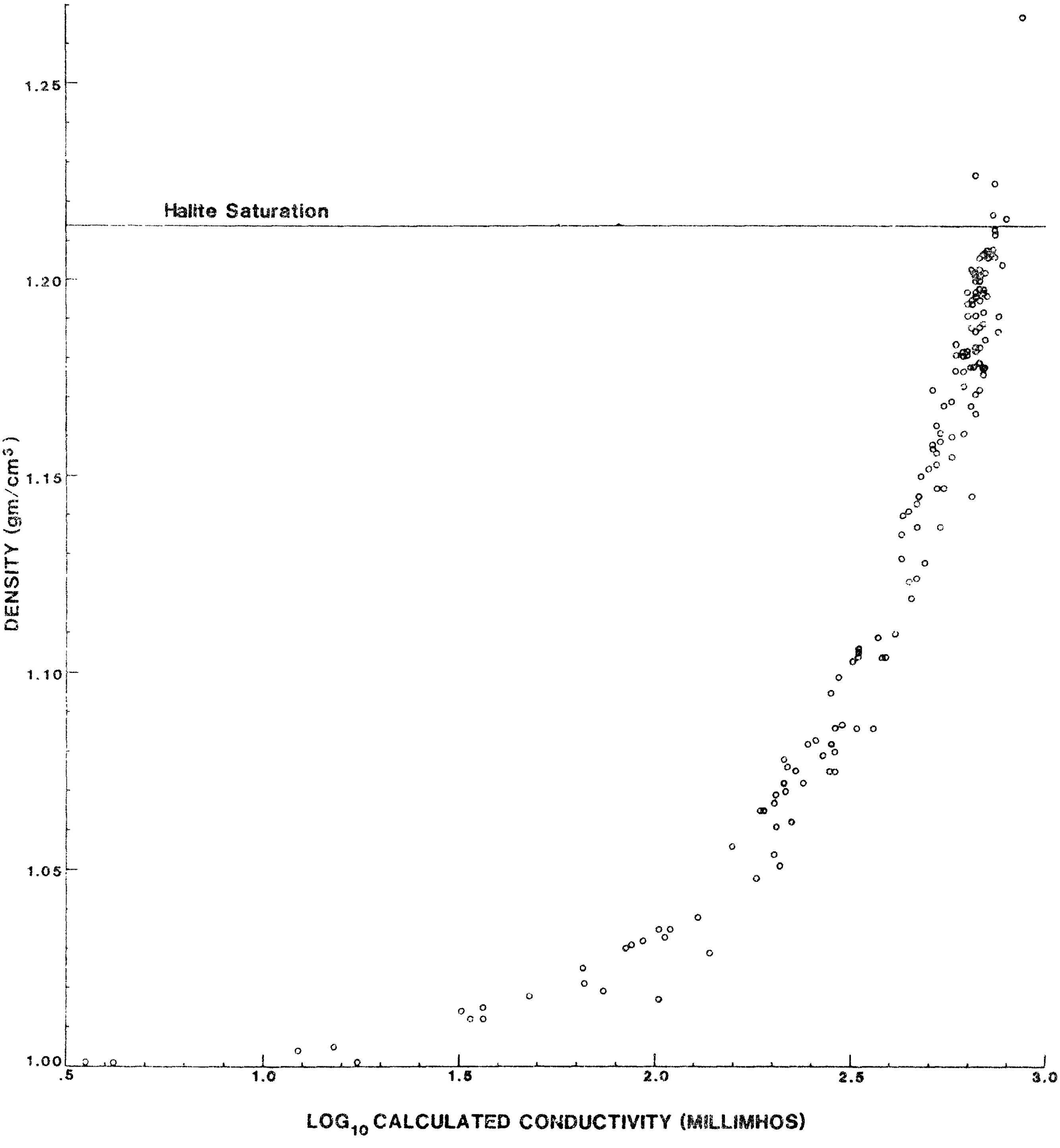

Figure 4.--Graph showing density and calculated conductivity of water samples. Halite saturation density from Usiglio (Clarke, 1924).

Economics

Most of the world's salt production is from evaporation of brines rather than from mining ancient salt deposits, and brines are used industrially, both directly and for the production of salt. Currently in Saudi Arabia, there is no known direct industrial utilization of brine, and only small amounts of salt are produced by brine evaporation. In the past, most of the salt used for human consumption in Saudi Arabia was produced in small-scale operations at such places as Sabkhah Murayqib, Aba al Hamam, and Sabkhah ar Riyas (pl. 1). In these operations, salt is scraped either from the sabkhah surface or from shallow pits, less than 30 cm deep, where ground water has evaporated and precipitated the salt. In most areas where salt is produced in this manner, the water table is less than 40 cm below the sabkhah surface, and the ground water is saturated or nearly saturated with halite.

Some major elements in sabkhah-related brines from the Eastern Province that are of potential industrial interest are potassium, magnesium, sodium, and chlorine. Outside Saudi Arabia these elements are utilized by industry either directly in brine or after they have been precipitated from the brine by further evaporation.

Potassium is produced from brine at Searles Lake, California, and also from the Dead Sea (Adams, 1975), where it has been produced commercially since 1932. The average potassium concentration in Dead Sea brines is 193 meq/l (Bentor, 1961), and the log of this concentration is approximately 2.29 (fig. 6). Although potassium concentrations are relatively high in sabkhah-related brines (fig. 6), few concentrations match or exceed the average concentration of Dead Sea brines.

Magnesium production from brines in the United States is primarily from seawater, but it has also been produced from subsurface brines. The average log magnesium concentration in the Arabian Gulf is about 2.17 meq/l, and the log magnesium concentration in the Dead Sea is about 3.54 meq/l (Bentor, 1961) (fig. 7). Most samples collected for this study contain more than twice the magnesium concentration of samples from the Arabian Gulf, but none contains as much magnesium as brines from the Dead Sea (fig. 7).

Wilson (1962) published a brief report concerning the feasibility of producing magnesium from brines in Saudi Arabia, in which he briefly discussed the possibility of using sabkhah-derived ground water as a source of magnesium. He indicated that subsurface brines that had been processed for production of magnesium in Michigan "lost out in the

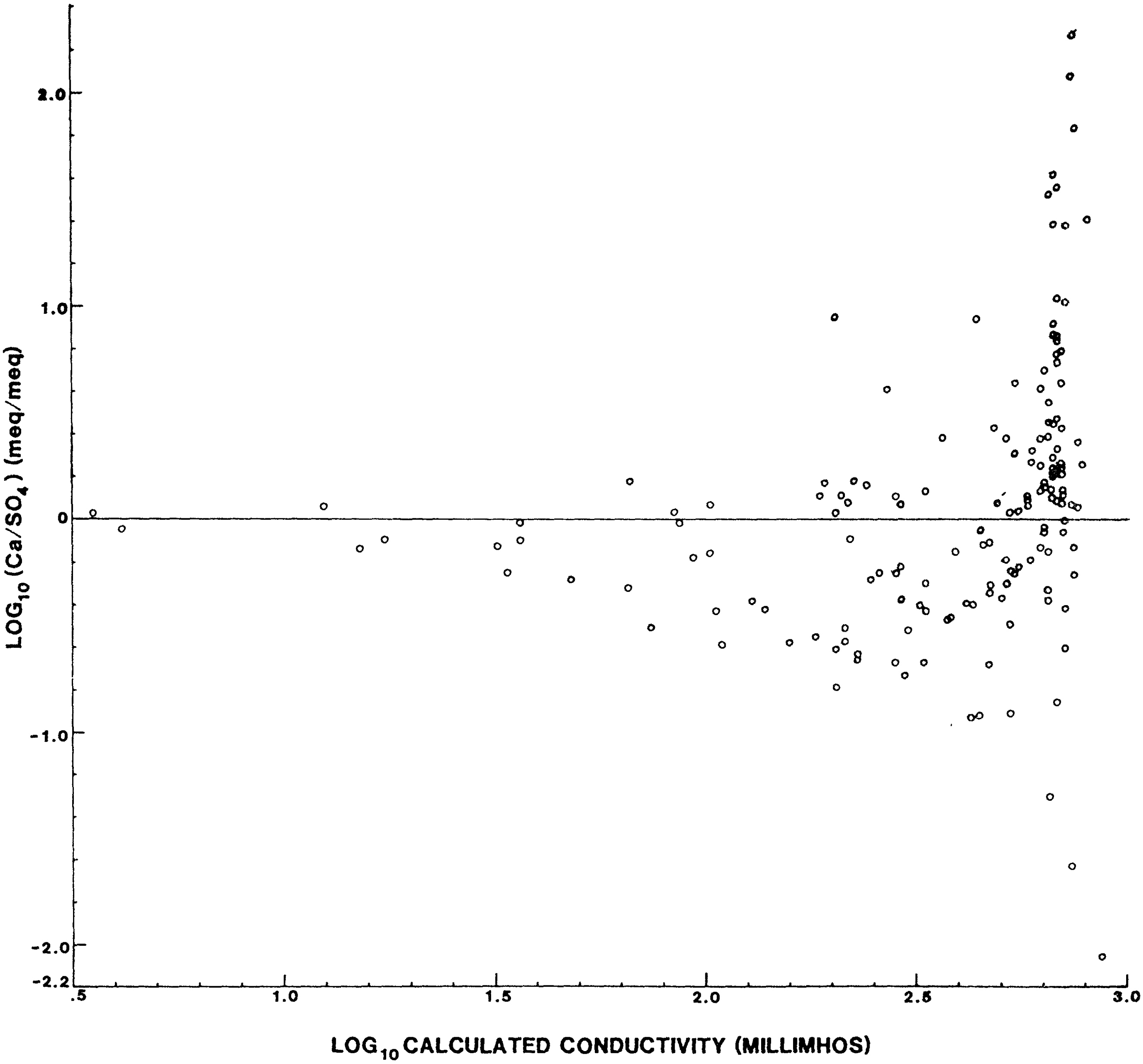

Figure 5.–Graph showing Ca/SO_4 ratio and calculated conductivity of water samples.

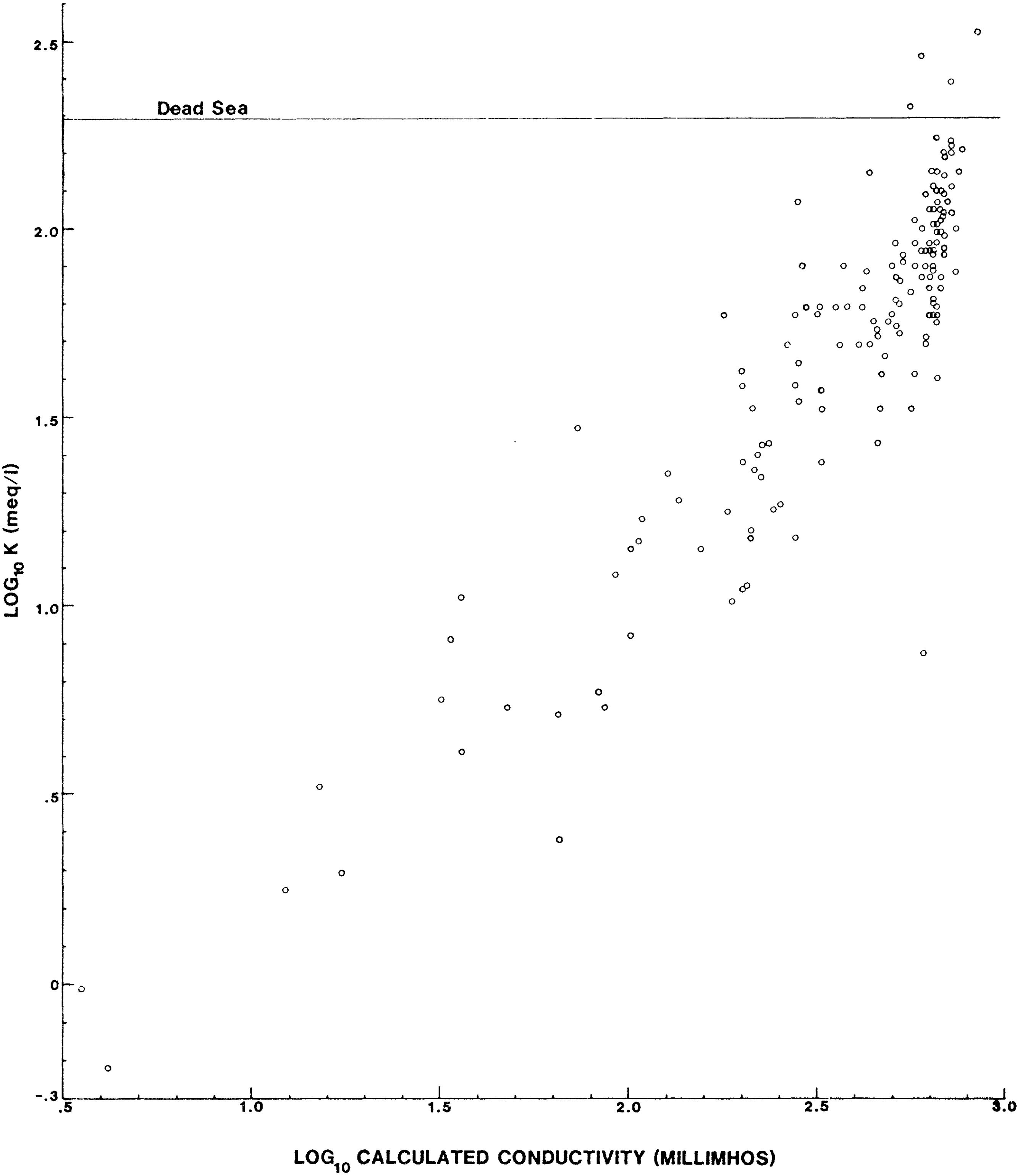

Figure 6.–Graph showing potassium content and calculated conductivity of water samples. Concentration of potassium in the Dead Sea from Bentor (1961).

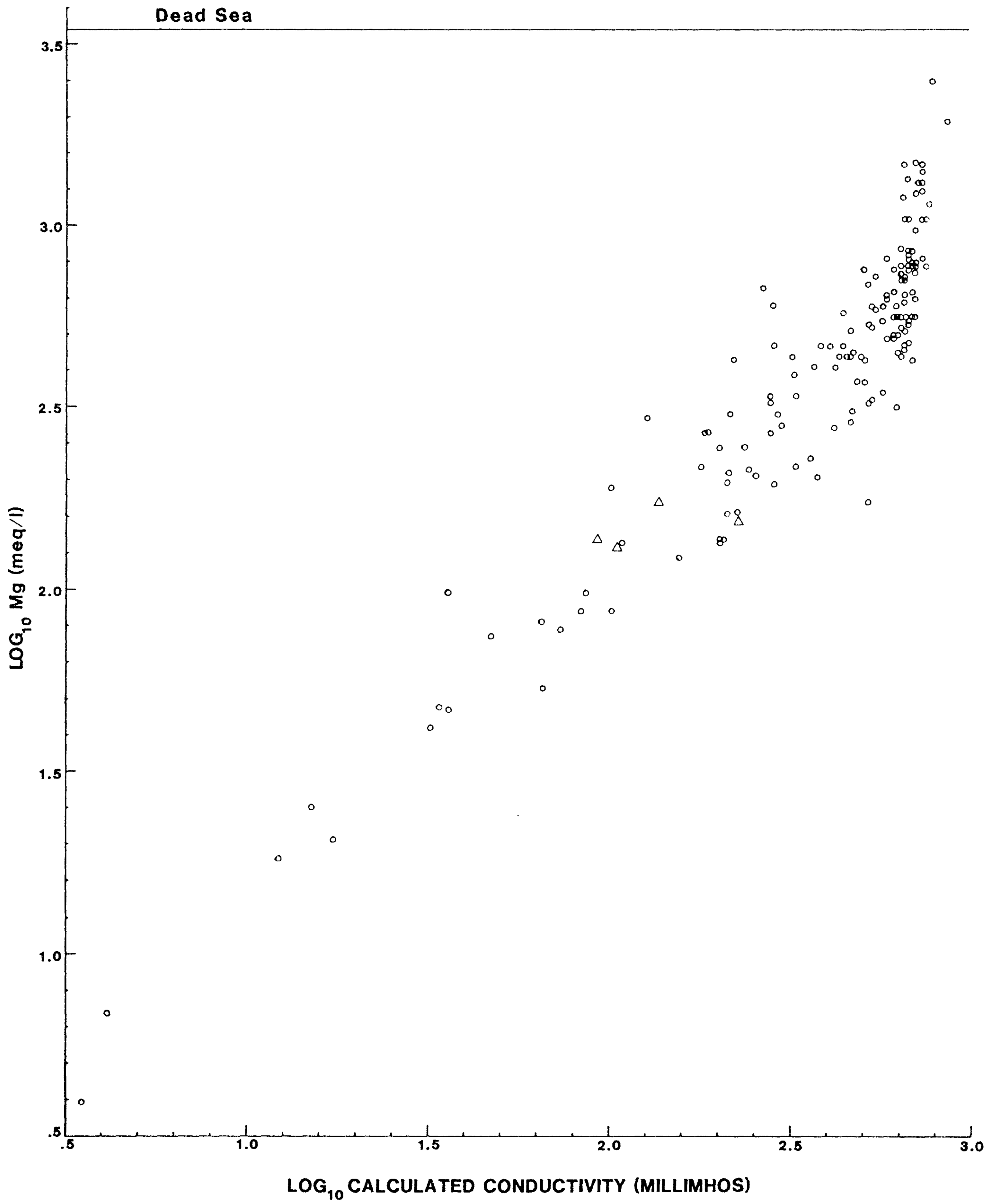

Figure 7.–Graph showing magnesium content and calculated conductivity of water samples. Triangles represent water samples from the Arabian Gulf. Concentration of magnesium in the Dead Sea from Bentor (1961).

U. S. to production of magnesium from seawater, and it is presumed without any further knowledge that the same factors which caused this switch there would also be operative here" (Wilson, 1962, p. 2). He also found that replenishment of ground water near the surface of the sabkhah where he dug a hole was slow.

As previously indicated, brines are not currently utilized on a large scale in Saudi Arabia, either directly or for the production of halite. However, much of the world's salt is derived from brines whose density is that of seawater (1.026 gm/cm^3) or less. Most of the samples collected for this study have densities that exceed that of water from the Arabian Gulf, and 59 samples have densities of 1.18 gm/cm^3 or greater (fig. 4) and are close to saturation with halite. An average water sample collected for this study has a density of 1.18 gm/cm^3 or greater and contains about 92 weight-percent sodium and chloride and only about 2 weight-percent sulfate (fig. 8).

In order to evaluate the economic potential of a sabkhah-related brine, it is necessary to determine how the chemistry of the brine varies with horizontal and vertical position in the sabkhah. Lateral changes of brine chemistry at the water table have been investigated on the coast of the United Arab Emirates (Butler, 1969; Patterson, 1972, unpublished data). These investigations indicate that away from the sabkhah margins toward the sabkhah center, the chloride concentration, and therefore the density, is high and relatively constant and that both the potassium and magnesium concentrations are relatively high but are more erratic than the chloride concentrations. At Sabkhah al Murayr, ground-water samples were collected at a spacing of approximately 1 km along two perpendicular sample lines (fig. 9). The northwest-trending sample line (line C-D) is approximately parallel to the Arabian Gulf coast in that area. Results of analyses of ground-water samples collected along the two sample lines (fig. 10) tend to support the findings of Butler (1969) and Patterson (1972, unpublished data) with regard to the horizontal variation of element concentrations at the water table.

The sampling in this study was restricted to the water table. However, on the coast of the United Arab Emirates, Patterson (1972, unpublished data) collected brine samples from depths of as much as 5 m below a sabkhah surface and 3.9 m below the water table. This sampling enabled Patterson to make some preliminary statements concerning changes in the concentrations of major elements in sabkhah-related brines in relation to depth below the water table. Although only relatively shallow penetrations of sabkhahs on the Arabian Peninsula have been reported, Patterson's work suggests a significant decrease in the amount of chloride, magnesium, and potassium in solution with depth.

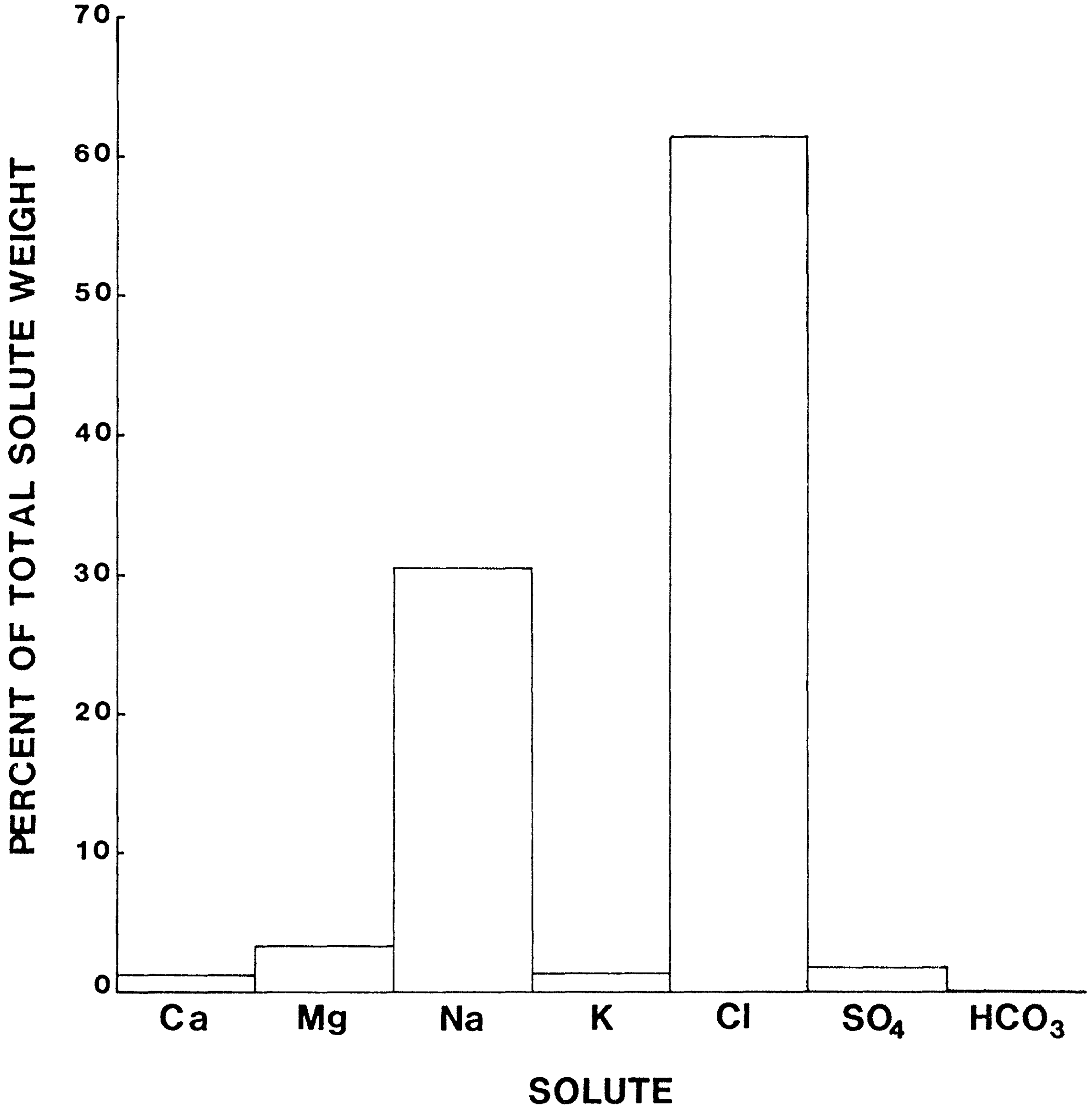

Figure 8.--Histogram showing relative proportions of major ions in an average water sample collected for this study with density 1.18 gm/cm^3 or greater.

CONCLUSIONS

Some preliminary conclusions are possible regarding the economic potential of sabkhahs in the Eastern Province.

Potassium concentrations in sabkhah-related brines are probably too low to be commercial. The concentrations of potassium in these brines are much less than the average concentration in brines in the Dead Sea (Bentor, 1961) or at Searles Lake, California (Adams, 1975). Whereas it might be possible to produce potassium-containing bitterns as a byproduct from the evaporation of seawater or sabkhah-related brines, it would probably not be economic to produce potassium as a primary product of brine evaporation.

Wilson (1962) stated two main objections to magnesium-metal production from sabkhah-related brines. He indicated that for unknown reasons magnesium metal production from subsurface brine in the United States "lost out" to magnesium metal production from seawater and also that replenishment of water pumped from pits in sabkhahs was slow. Although a few sabkhahs contain some silt- and clay-size sediments, the most common detrital sediment in the sabkhahs visited during this study was eolian sand. Replenishment of ground water did not appear to be a problem in most sabkhahs visited.

As indicated by Wilson (1962), magnesium metal is not currently produced from the subsurface brines in Michigan; however, magnesium metal can be economically produced from brines other than seawater, such as brines of Great Salt Lake, Utah (Wicken and Duncan, 1975). The brines in Michigan are used to produce magnesium compounds rather than magnesium metal. Hill and Prosser (1981) indicated that 64 percent of the magnesium compounds produced in the United States in 1979 was produced from Michigan's subsurface brines. Several companies, such as Dow Chemical Company, Martin Marietta Chemicals, and Velsical Chemical Corporation, produce magnesium compounds from the Michigan brines. The economic factors that influenced the decision of these companies to produce magnesium compounds rather than magnesium metal are unknown to the author. Although the type of magnesium product is at least partially determined by local economic factors, most brines with high concentrations of magnesium and sufficient volume have the potential to produce magnesium products.

Because magnesium is commonly produced from seawater and most brine samples collected from the east-coastal belt contain twice as much or more magnesium as Arabian Gulf water, the magnesium concentrations in many sabkhah-related brines are high enough to be of interest. However, one of the most

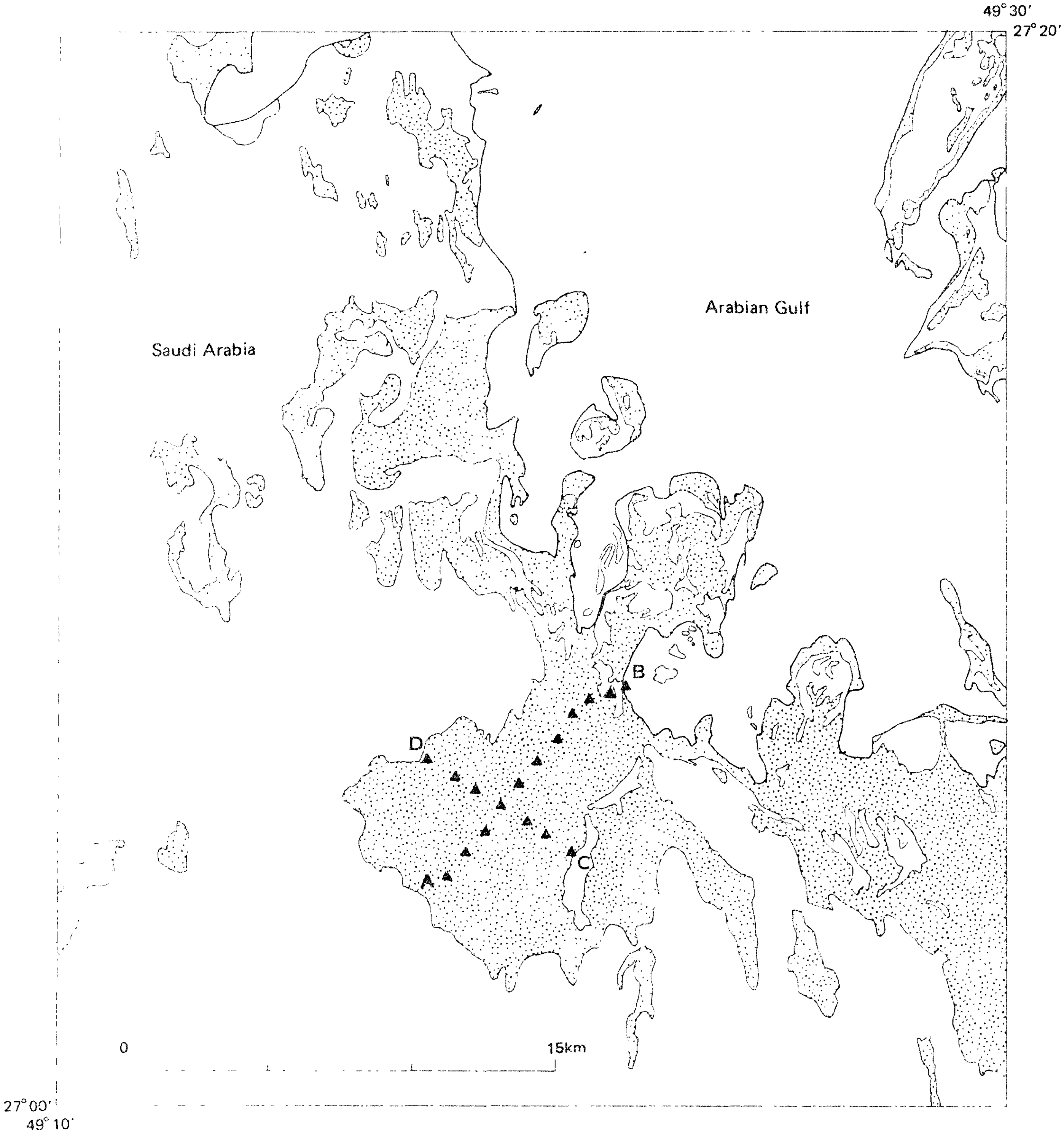

Figure 9.--Map showing location of water samples (triangles) collected from Sabkhah al Murayr. The water sample collected at the northeastern end of sample line A-B is seawater from the Arabian Gulf. Stipple pattern indicates sabkhah areas.

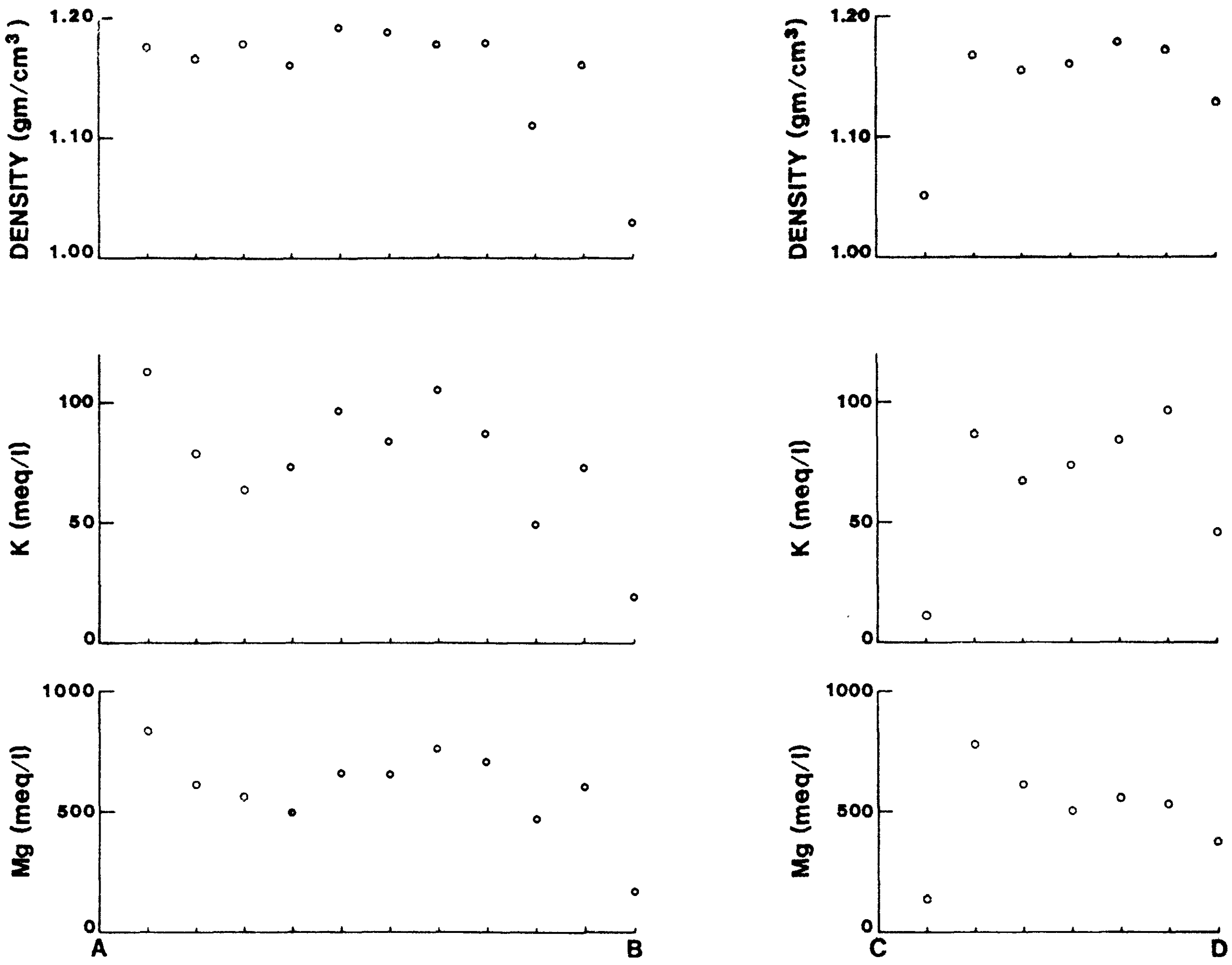

Figure 10.–Graphs showing potassium and magnesium concentrations and density of water samples collected on and near Sabkhah al Murayr. The sample collected from the northeastern end of sample line A-B is seawater from the Arabian Gulf. All other water samples were collected from holes dug to the water table.

serious impediments to magnesium production from sabkhah-related brines is the possibility that the relatively high magnesium concentrations found in brines at the water table may not extend more than a meter or two below this surface. This possible failure of the high surface concentration to extend downward is also a potential problem in producing brines for direct utilization or, after further evaporation, for the production of salt. Currently, only limited information is available about the change in brine chemistry with depth below the water table, and further studies are warranted.

A search for shallow salt bodies without surface exposure, such as the one at the Jayb Uwayyid sabkhah (fig. 2), should be attempted. The Jayb Uwayyid salt deposit has some potential for commercial development, either by direct mining or by utilization of the halite-saturated brine. Unlike other sabkhah brines, the sodium and chloride concentrations of a brine pumped from above the salt body at Jayb Uwayyid should not change greatly with depth, and a large volume of halite-saturated brine could probably be produced from this deposit.

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