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SULFUR SPECIATION, SULFUR ISOTOPY, AND ELEMENTAL ANALYSES OF WATER-COLUMN, PORE WATER, AND SEDIMENT SAMPLES FROM SOAP LAKE, WASHINGTON

by

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Introduction

Soap Lake, Washington (Fig. 1) is an example of a modern depositional environment that is characterized by having extremely high concentrations of Na^+, CO_3^{2-}, HCO_3^-, Cl^-, SO_4^{2-}, and biogenic HS^-. Little is known about the sulfur geochemistry in such highly saline and alkaline systems. The purpose of this study is to characterize the sulfur geochemistry of samples from the water column, the sediment, and pore water extracted from sediments in Soap Lake.

Soap Lake is meromictic and is located in east central Washington. It is the terminal lake in a southwesterly trending series of residual lakes formed when the Okanagon Lobe of the Cordilleran Ice Sheet diverted the Columbia River during the Pleistocene. This diversion of the Columbia River pushed the waters into a new riverbed forming the Grand Coulee, a steep-sided valley that is 70 km long and 1-2 km wide. Grand Coulee is the westernmost channel in the channeled scablands of eastern Washington (Bretz, 1932; Bretz and others, 1956). Bretz (1932) provides a complete description of the Grand Coulee as well as the history of its formation. As the Columbia River returned to its preglacial channel, a series of residual lakes remained in the Grand Coulee. The lakes are underlain by the Miocene Yakima basalt (Gilkeson, 1962). This basalt rises to an elevation in the southern portion of the Coulee that is above the lake levels, effectively closing the lake series to external drainage. Water recharge into the lakes is from groundwater seepage and precipitation; yearly evaporation exceeds the input causing the lakes to become more concentrated in dissolved salts. It has been estimated that this progressive concentration has been occurring for the last 2,000 years (Friedman and Redfield, 1971) bringing the lake waters to their maximum content of total dissolved solids (TDS) around the year 1950. At that time, water diversion by the Columbia Basin Irrigation Project caused dilution of the lakes. Interception wells drilled to the north and south of Soap Lake in 1958 halted the dilution of Soap Lake, but the other lakes are still being diluted.

Soap Lake is highly alkaline (pH=9.8) and high in primary productivity, 391 g C m^{-2} annually, (Walker, 1975; and Friedman and Redfield, 1971). Surface area is 339 hectares and mean and maximum depths are 10 and 27 meters, respectively. The mixolimnion, the upper, less dense, circulating waters of a meromictic lake, extends to 17 meters and contains approximately 17.5-18 g/L TDS with Na^+, K^+, HCO_3^-, CO_3^{2-}, SO_4^{2-}, and Cl^- ions comprising the major species (Walker, 1974). The much more concentrated waters of the monimolimnion (the noncirculating bottom water of a meromictic lake), below the chemocline at 20 m, are an euxinic brine (HS^- containing) having a TDS content of about 141-142 g/L (Edmondson, 1963, Friedman and Redfield, 1971). High concentrations of sulfate coupled with anoxic conditions in the monimolimnion provide ideal conditions for sulfate-reducing bacteria and indeed, concentrations of dissolved HS^- as high as 140 mM (this study) have been measured in this layer. To the authors' knowledge, this is the highest dissolved sulfide concentration as yet reported for a natural water.

Field Methods

Two sediment cores were collected in August, 1986 using a gravity corer. Core I (28 cm in length) was collected in 8.5 m of water in sediments above the monimolimnion and core II (70 cm long) was collected in 25 m of water in sediments below the monimolimnion (Fig. 1). On retrieval, each core was carefully extruded and subsampled under aerobic conditions at approximately 3-4 cm intervals. Subsamples for core II were placed in 100 cm^3 centrifuge tubes, the atmosphere in the tube was replaced with N_2, and the centrifuge tube was capped and sealed for transport back to the laboratory. Subsamples of core I were processed in the field. The subsample was placed in a centrifuge tube under nitrogen and centrifuged at 10,000 rpm for 10 minutes to separate the pore water from the accompanying sediment. The pore water obtained was extracted from the centrifuge tube with a 30 cm^3 Luer-Loc® syringe and Tygon® tubing. The Tygon® tubing was then removed and a 0.45 µm Luer-Lok® filter cartridge was attached to the syringe and the pore water was filtered through the cartridge. A portion of the filtrate was placed in a 30 ml preweighed polyethylene bottle which contained approximately 1.5 g cadmium acetate thus precipitating any sulfide species as CdS. Another portion of the filtered pore water was placed in a preweighed 30 ml polyethylene bottle and acidified with 0.25 ml of concentrated hydrochloric acid (HCl). The sediment and water remaining in the centrifuge tube were put into a preweighed 60 ml polyethylene bottle. All samples were placed on dry ice and transported to the laboratory.

Samples from the water column of Soap Lake were collected with a Van Dorn bottle at two meter intervals. At each interval, one subsample was placed into a preweighed 125 ml polyethylene bottle to which 5 g of cadmium acetate had been added. Another subsample was placed in a preweighed 125 ml bottle for elemental analysis.

Laboratory Methods

All samples were reweighed on return to the laboratory. These weights and subsequent weights taken during the analyses allowed determination of sample weights and % water loss in the sediment samples. The samples from sediment core II which were placed in centrifuge tubes in the field were centrifuged at 10-12,000 rpm for 1.5-2 hours on return to the laboratory. The separated pore water was then treated exactly as the pore water from core I. After the pore water had been removed, an attempt was made to wash the residual pore water from the sediments by adding distilled water to the sediment in the tube, mixing, centrifuging and decanting the water. However, after several rinsings, significant amounts of dissolved salts (detected by addition of $AgNO_3$ to the rinses of the pore water) still remained in the rinses and this method was abandoned. Eight samples from core II were processed in this manner and are noted as such in the data tables. All handling of the samples except the withdrawal of the pore water was done in a nitrogen-filled glove bag.

Carbon analysis

Sediment samples from cores I and II were placed in a vacuum oven, dried under vacuum, and reweighed. The samples were then placed in a glove bag under N_2 and ground with a mortar and pestle. A subsample of the ground sediment was taken for total carbon and organic carbon analysis. Total carbon and organic carbon for the sediments were determined by Leco® furnace combustion. Approximately 50 mg of dry sediment was weighed in a Leco® fusion crucible, treated with 6N HCl until effervescence ceased, dried in an oven at about 50°C overnight, and combusted in the Leco® furnace to determine the organic carbon. Total carbon was determined by combusting approximately 50 mg of untreated dry sediment sample and inorganic carbon was obtained by the difference between the measured total and organic carbon.

Sulfur speciation

Quantitative analysis of sulfur species was performed on remaining splits of the dried sediments and on the water column and pore water subsamples that had been placed in bottles containing cadmium acetate. Details of the speciation method are given in Tuttle and others (1986). In the sulfur speciation scheme, a weighed sample is placed in a reaction vessel, 6N HCl is added and heat is applied. The acid-volatile sulfur species, which include all species except iron disulfides, organically-bound sulfur, and inorganic sulfate, are converted to H_2S which is collected as Ag_2S. The inorganic sulfate in the sediment, which is leached by the acid in the previous step and which remains in the HCl solution, is precipitated and collected as $BaSO_4$. The remaining insoluble sediment is then removed from the HCl solution by filtration and reacted with a solution containing 1M Cr^{2+} to reduce sulfur in the disulfides to H_2S which is collected as Ag_2S. The remaining sediment is then fused with Eschka's mixture in a modification of ASTM method D3177 (1977) to release the organically bound sulfur which is precipitated and collected as $BaSO_4$. Solutions from the 6N HCl and the Cr^{+2} reduction steps were analyzed for Fe content using standard methods for atomic absorption spectrophotometry. Dilutions of these samples and standard solutions of known concentrations that were dissolved in similar matrices were analyzed by flame atomic absorption spectrophotometry; the concentrations of Fe were obtained by comparison of the samples to the standards.

Sulfur isotopes

The isotopic compositions of the $BaSO_4$ and Ag_2S precipitates collected from the sulfur speciation analyses were determined. The Ag_2S is converted to SO_2 by slowly combusting a 20 mg charge of sulfide with 50 mg degassed CuO at 1025°C in an evacuated combustion-vacuum line. The SO_2 is collected, volumetrically measured, and its isotopic composition determined on a high resolution, six inch, 60 degree sector mass spectrometer. All corrections for oxygen isotopic composition of the SO_2 and conversion to $\delta^{34}S_{CDT}$ (CDT, measured relative to Canyon Diablo troilite) are handled by a computer interfaced to the mass spectrometer. $BaSO_4$ is decomposed to SO_2 utilizing a quartz reduction process which allows isotopic equilibration of the SO_2 with the quartz sand. The remainder of the collection and measurement is essentially the same as that for Ag_2S.

Elemental analysis

Elemental analysis by inductively coupled plasma-atomic emission spectrometry (ICP) was performed on the pore water, water column, and sediment samples. A detailed description of ICP analytical wavelengths and instrumental operating conditions is given in Crock and others (1983). Special care was necessary with these samples to minimize spectral line overlap and background shifts because of the high sodium content. One requirement for sample analysis is that the samples must be in solution with a low pH; therefore, all the samples were pretreated prior to analysis.

For the water column, a 20 g aliquot was acidified with 2 mL of concentrated HCl, heated on a hotplate until dry and diluted to a final mass of 20 g with 3 N HCl. The same basic pretreatment was performed on the pore water samples except the masses were much smaller (5 g) because of the smaller amount of sample available. Sediment samples were dissolved using a combination of hydrofluoric (HF), HCl, nitric (HNO_3), and perchloric acids ($HClO_4$). Generally, a 0.1 g sample was digested with the above acids on a hotplate in a teflon vessel and diluted by weight to 10 g using 1% HNO_3. A detailed description of the sample dissolution procedure can be found in Crock and others (1983). Acid blanks, sample duplicates, and rock and sediment standards were processed with the sediment samples for quality assurance of the dissolution and analysis.

The F^-, NO_3^-, and SO_4^{2-} anions were determined by ion chromatography (IC) on the pore water and water column samples. An in-depth description of anion analysis by IC in waters is given in Fishman and Pyen (1979). The specific conductance was measured for the anions of interest in the samples and for standards of known anion concentration. Concentrations of the anions in the samples were determined by comparison of the samples to the standards.

Results

Sulfur speciation and sulfur isotopy

Results of the sulfur speciation analyses for samples from the water column are presented in Table 1. The concentration of dissolved sulfide species in the water column increases from 10 mM at 20 m to 140 mM at 24 m. Above 20 m, no dissolved sulfide species were detected (<0.01 weight % S of dry sediment). Concentrations of sulfate in the water column showed a slight increase from 20 mM at the surface to 44 mM at 12 m, declining in the chemocline to 16 mM and increasing dramatically to values of 360 mM in the hypolimnion. $\delta^{34}S$ values for the dissolved sulfide species in the hypolimnion show evidence of bacterial fractionation with values averaging -28 per mil. The values of $\delta^{34}S$ for the sulfate in the water column increase from 10 per mil at the surface to 25 per mil at 24 m.

Table 2 contains results of the analyses of pore water sulfur species in the two cores. Core I, from the oxic portion of the lake has sulfide concentrations increasing from 0.8 mM at the sediment-water interface to 4 mM at 27 cm. The increase is attributed to production of sulfide in the sediment by sulfate-reducing bacteria. The concentrations of sulfide in the pore waters of core II are much higher and nearly constant with a mean of 113 mM resulting from incorporation of HS^- from the water column during sediment deposition. The sulfate concentration of the pore water in core I is fairly constant, averaging 35 mM, similar to the sulfate concentration in the mixolimnion. Core II has pore water sulfate concentrations averaging 270 mM and showing a slight increase with depth.

Values of $\delta^{34}S$ of pore water sulfides in core I are constant at about -44 per mil, a fractionation of approximately 60 per mil from $\delta^{34}S$ values of pore water sulfate. Sulfate increases from 13 per mil in the shallowest sediment sample to 21 per mil at 27 cm. Sulfide $\delta^{34}S$ values in core II reflect $\delta^{34}S$

values in the monimolimnion of the water column and are constant at -26 per mil. The sulfate $\delta^{34}S$ values in the pore water are 25 per mil, also reflective of the values of sulfate found in the water column.

Results of sulfur speciation of sediments from core I and II are presented in Table 3. Concentrations of mineral sulfides in core I (both acid-volatile and disulfides) are very low and range from 0.002 wt % monosulfide to 0.059 wt. % as the disulfide. The amount of sulfur organically bound is nearly constant throughout core I at 0.035 wt %. Sulfur species are more abundant in core II, but are still relatively low. The concentrations of acid-volatile sulfides and organically bound sulfur do not show any trend in the core and average 0.025 and 0.090 wt. %, respectively. Disulfide, however, does increase with depth from 0.03 % at the top of the core to 0.22 wt. % at the bottom.

No $\delta^{34}S$ values for acid-volatile sulfides in core I were determined because of the very low abundance of acid-volatile sulfides in these samples. The values of $\delta^{34}S$ in the disulfide fraction vary throughout the core. The organically bound sulfur had isotope values of -13 per mil at the surface decreasing to -23 per mil at 27 cm. $\delta^{34}S$ values of the species in core II all decrease with depth. The values of the isotopes appear to divide the sediments of core II into two distinct segments at about 46 cm depth. $\delta^{34}S$ values for the acid-volatile sulfides are about -20 per mil above 46 cm and decrease to -28 per mil with depth. The mineral disulfides are also heavier above 46 cm with a $\delta^{34}S$ value of -15 per mil as opposed to a value of -25 per mil at depth. The organically bound sulfur has isotope values of -12 per mil above 46 cm and -17 per mil below this depth.

Carbon Abundances

The amount of total carbon in both cores is variable, but generally decreases with depth. The percentages of the organic and carbonate fractions also reflect this trend. Values of total carbon in core I range from 4.4 % to 8.6 wt. % while in core II values are higher ranging from 6.2 to 20 wt. %. This difference in organic carbon between the cores is probably the result of increased dilution of the organic matter content of core I from input of inorganic detritus as well as preservation of organic matter in core II because of the euxinic conditions. The organic carbon in both core I and core II constitutes more than 50 % of the total carbon with a mean of 61% in core I and a mean of 76% in core II.

Elemental Concentrations

Elemental composition values for samples from the water column are given in Tables 4 and 7. Many of the values of elements analyzed for are reported as less than because the concentrations in the sample were lower than the detection limit of the method used. Elements for which the values were less than throughout the core are listed in Table 7 with the maximum less than value given. Concentrations of elements or species which were above the detection limit show an increase below 18 m as the monimolimnion is entered and continue to increase to their maximum within this layer. The more soluble ions such as K^+, Na^+, and SO_4^{2-} show the greatest increase as expected.

Concentrations of ions in the pore water samples of the two cores (Tables

5 and 7) reflect abundances in the water column of the associated layer, the mixolimnion for core I and monimolimnion for core II. Values of elemental concentrations in core II therefore are higher than values in core I with the more soluble ions again indicating the greatest increase. These ions also tend to increase with depth in the cores. Table 7 contains the elements having less than values for the entire core.

The element concentrations in the sediment samples from the two Soap Lake cores are found in Tables 6 and 7 and must be viewed cautiously because of the procedures used to obtain the subsample on which the ICP analyses were performed. All of the samples from core I and all except the eight from core II noted in Tables 3 and 6 were dried with a varying amount of pore water remaining in the sample. The weight of the dried sample thus contains a percentage of salts derived from the evaporated pore water that is not originally a portion of the solid phase. This added weight also contributes a dilution effect to the concentrations of elements in the sediments excluding the very soluble ions such as Na^+ and K^+ which will of course show an increase as expected. In order to closely study any trends occurring in the sediment samples, corrections would have to be applied to enable comparisons within each core, between the two cores, and with any data from other studies. The percent water loss from evaporative drying and the amount of pore water that remained in the sediment upon drying is given in Table 3 for core I and for the eight samples in core II processed without rinsing. No attempt to apply these corrections is made in this presentation of the data and except for some very general observations, no discussion of the sediment values will be presented. The concentrations of elements and species in core II appear to divide the sediments of core II into two distinct segments at about 46 cm depth. This difference in the sediments of core II was noted in the previous discussion of the sulfur speciation and isotopy data. It may also be noted that some trends of groups of elements are apparent, but without correcting the values, the significance of these trends is unclear. Table 7 contains elements for which all the values in the cores were reported as less than.

Summary

The sulfur geochemical data and the elemental composition data for Soap Lake samples are both predictable and surprising. Clear differences are observable between the samples from the non-euxinic core overlain by the mixolimnion and the euxinic core from 25 m in the waters of the monimolimnion. Pore water samples reflect the increased dissolved solid concentration of the lake waters in core II as well as extremely high levels of HS^- as expected. The sulfur concentrations and $\delta^{34}S$ values of the various forms of sulfur in the samples offer surprising results. The concentrations of mineral sulfides in the sediments are low considering the relatively large amounts of dissolved sulfide and iron in the sediment. This indicates an inhibition of rapid iron sulfidization in Soap Lake. In addition, the isotope values of the forms of sulfur indicate that the mechanism of mineral sulfide formation may be complex because of the unexpected isotopically heavy mineral sulfides relative to accompanying pore water H_2S $\delta^{34}S$ values.

Further study of the data and additional experimental work is necessary and is proceeding in order to explain these results. The role of the high pH in this system in controlling geochemical processes needs further investigation and controlled laboratory experiments are being conducted to accomplish this. Likewise, the reactivity of iron, association of other mineral sulfide-forming metals, including Cu, Pb, and Zn, the physical structure of the sediments, and the importance of the chemocline and internal seiches must be studied to gain a complete understanding of the sulfur geochemistry in this system. A more detailed study of the organic matter present in Soap Lake would also yield valuable clues to its role in the formation of mineral sulfides: is it complexing the iron or contributing in some other manner to the inhibition of rapid iron sulfide formation? In summary, this study has provided valuable data concerning the sulfur geochemistry of the Soap Lake system and some preliminary observations can be made from it. However, as is the case with many geochemical investigations, the data obtained from Soap Lake raises more questions and hopefully, additional work will allow a greater understanding of modern systems of this nature.

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References Cited

ASTM Annual Book of Standards, part 26, 1977, Total sulfur in the analysis sample of coal and coke: American Society for Testing Materials, Philadelphia, p. 322-326.

Bretz, J.H., 1932, The Grand Coulee: American Geographical Society Special Publication No. 15, 89 p.

Bretz, J.H., Smith, H.T.U., and Neff, G.E., 1956, Channeled scabland of Washington: New data and interpretations: Bulletin of the Geological Society of America, v. 67, p. 957-1049.

Crock, J.G., Lichte, F.E., and Briggs, P.H., 1983, Determination of elements in National Bureau of Standards geological reference materials SRM 278 Obsidian and SRM 688 basalt by inductively coupled argon plasma--atomic emission spectroscopy: Geostandards Newsletter, v. 7, no. 2, p. 335-340.

Edmondson, W.T., 1963, Pacific Coast and Great Basin, in D. G. Frey, ed., Limnology in North America: Madison, Wisconsin, Univ. Wisconsin Press, p. 371-392.

Edmondson, W.T. and Anderson, G.C., 1965, Some features of saline lakes in central Washington: Limnol. Oceanogr., suppl. to 10, R87-R96.

Fishman, M.J. and Pyen, G., 1979, Determination of selected anions in water by ion chromatography: U.S. Geological Survey Water-Resources Investigations 79-101, p. 1-30.

Friedman, I., and Redfield, A.C., 1971, A model of the hydrology of the lakes of the lower Grand Coulee, Washington: Water Resources Research v. 7, no. 4, p. 874-898.

Gilkeson, R.A., 1962, Washington soils and related physiography--Columbia Basin Irrigation Project, Washington Agr. Exp. Sta. Circ. 327, 5 p.

Tuttle, M.L., Goldhaber, M.G., and Williamson, D.L., 1986, An analytical scheme for determining forms of sulphur in oil shales and associated rocks: Talanta, v. 33, no. 12, p. 953-961.

Walker, K.F., 1974, The stability of meromictic lakes in central Washington: Limnology and Oceanography, v. 19, no. 2, p. 209-222.

Walker, K.F., 1975, The seasonal phytoplankton cycles of two saline lakes in Central Washington: Limnol. Oceanogr., vol. 20, no. 1, p. 40-53.

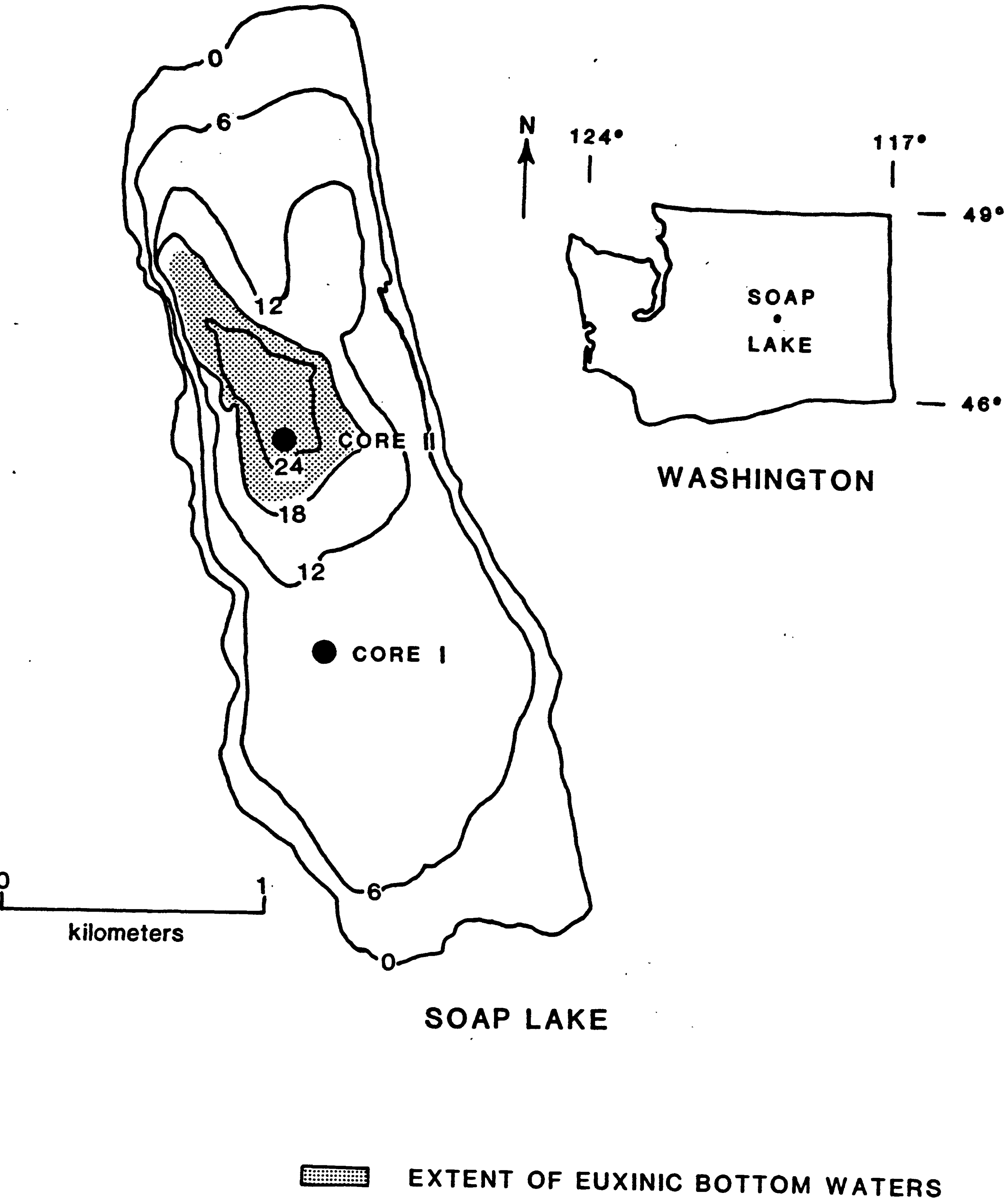

Figure 1. Index and bathymetric map of Soap Lake (after Edmondson and Anderson, 1965) showing core locations. Contours are in meters.

Table 1. Sulfur speciation and sulfur isotopic data for water column samples from Soap Lake.

WATER COLUMN DEPTH m	DENSITY g/ml	SULFIDE mM	SULFATE mM	δ 34 S SULFIDE per mil	δ 34 S SULFATE per mil
0	1.003	0	26		10.1
2	1.005	0	21		
4	1.005	0	23		
6	1.002	0	30		
8	1.003	0	34		10.1
10	1.005	0	42		
12	1.004	0	44		
14	1.003	0	30		
16	1.003	0.018	19		
18	1.007	0.043	16		16.5
20	1.022	10	49	-32.1	
22	1.072	110	360	-28.2	
23	1.111	130	340	-28.1	25.5
24	1.105	140	320	-27.6	25.5

Table 2. Sulfur speciation and sulfur isotopic data for pore water samples from Soap Lake. Depths are cm below sediment-water interface.

CORE	DEPTH cm	DENSITY g/ml	SULFIDE mM	SULFATE mM	δ 34 S SULFIDE per mil	δ 34 S SULFATE per mil
I	2	1.003	0.75	31		13.2
I	5	1.005	1.3	30		
I	8	1.016	0.51	31		14.6
I	11	1.012	2.2	33	-44.1	
I	14	1.010	1.8	34	-44.0	17.6
I	17	1.006	2.8	37	-43.8	
I	20	1.010	3.4	39		20.6
I	24	1.007	3.6	36		
I	27	1.014	3.9	37	-42.4	21.0
II	2	1.104	110	260	-26.5	
II	5	1.102	110	250		25.5
II	7	1.095	110	250		
II	16	1.112	110	270		
II	19	1.109	120	270		
II	26	1.098	120	260		
II	29	1.114	120	270	-26.3	
II	35	1.109	110	270	-26.4	
II	37	1.113	110	280	-26.3	
II	44	1.118	120	280		
II	46	1.102	120	280	-26.5	
II	49	1.103	110	280		
II	52	1.110	120	290		
II	59	1.099	120	290		
II	61	1.106	120	280		
II	68	1.102	110	280	-26.7	23.2

Table 3. Sulfur speciation and sulfur isotopic data for sediment samples from Soap Lake. Depths are cm below sediment-water interface. Concentrations are reported on a dry weight basis.

CORE	DEPTH cm	ACID-VOLATILE SULFIDE WT. %	DISULFIDE WT. %	TOTAL SULFIDE WT. %	ORGANIC S WT. %	TOTAL C WT. %
I	2	0.002	0.016	0.018	0.032	8.6
I	5	0.002	0.014	0.016	0.033	6.7
I	8	0.001	0.044	0.045	0.030	5.3
I	11	0.005	0.059	0.064	0.032	5.4
I	14	0.008	0.027	0.035	0.034	6.3
I	17	0.005	0.018	0.023	0.036	5.7
I	20	0.008	0.026	0.034	0.036	4.4
I	24	0.004	0.044	0.048	0.039	4.5
I	27	0.003	0.048	0.051	0.040	4.7
II	2	0.018	0.023	0.041	0.086	16
II	5	0.030	0.032	0.062	0.081	15
II	7	0.020	0.025	0.045	0.053	13
II	16	0.018	0.020	0.038	0.034	13
II	*19	0.020	0.033	0.053	0.11	20
II	*26	0.016	0.034	0.050	0.069	17
II	29	0.023	0.033	0.056	0.043	12
II	*35	0.016	0.051	0.067	0.094	18
II	37	0.025	0.025	0.050	0.061	12
II	*44	0.033	0.033	0.066	0.096	16
II	*46	0.026	0.12	0.15	0.11	12
II	49	0.027	0.10	0.13	0.083	9.7
II	*52	0.024	0.13	0.16	0.094	8.1
II	59	0.065	0.15	0.22	0.068	6.6
II	*61	0.027	0.15	0.18	0.090	7.2
II	*68	0.029	0.23	0.26	0.088	6.2

* These samples were rinsed with distilled water prior to drying.

Table 3. Continued

CORE	DEPTH cm	ORGANIC C WT. %	CARBONATE C WT. %	ACID SOLUBLE Fe WT. %	Cr REDUCED Fe ppm	WATER LOSS %
I	2	4.8	3.9	1.3	650	88
I	5	5.1	1.6	1.8	540	85
I	8	3.4	1.8	2.1	460	80
I	11	3.3	2.0	2.3	440	84
I	14	3.9	2.4	2.1	330	87
I	17	3.3	2.4	1.8	280	81
I	20	2.5	1.9	2.0	510	75
I	24	2.6	1.9	1.9	510	75
I	27	2.8	1.8	1.9	570	75
II	2	12	3.8	0.63	410	97
II	5	12	3.0	0.55	480	97
II	7	7.9	4.7	0.62	420	97
II	16	9.7	3.8	0.61	210	93
II	*19	20	0	1.2	360	97
II	*26	14	2.4	1.2	420	95
II	29	7.8	4.1	0.61	360	91
II	*35	11	6.3	0.75	560	95
II	37	7.6	4.9	0.69	130	92
II	*44	13	2.5	1.4	330	98
II	*46	11	1.3	2.1	390	96
II	49	6.8	2.9	1.2	340	92
II	*52	5.7	2.3	2.6	390	93
II	59	4.5	2.1	2.2	350	95
II	*61	6.3	0.86	2.4	490	96
II	*68	5.0	1.3	2.8	330	95

* These samples were rinsed with distilled water prior to drying.

Table 3. Continued

CORE	DEPTH cm	PORE WATER ADDED g	δ 34 S ACID VOLATILE per mil	δ 34 S DISULFIDE per mil	δ 34 S ORGANIC S per mil
I	2	11			-13.3
I	5	16			
I	8	16		-31.5	-20.3
I	11	17		-41.6	
I	14	13			
I	17	15			-22.4
I	20	14		-25.3	
I	24	14			-23.1
I	27	14		-18.9	
II	2	3.3			
II	5	3.5			
II	7	4.0			
II	16	10	-19.2	-15.1	-11.8
II	*19				-13.4
II	*26				
II	29	13	-20.6	-12.9	-12.1
II	*35			-15.3	
II	37	12			
II	*44				
II	*46			-24.0	-16.9
II	49	7.4	-23.6	-23.8	
II	*52				
II	59	4.0	-25.9	-24.5	-17.5
II	*61				
II	*68		-27.8	-25.1	

These samples were rinsed with distilled water prior to drying.

Table 4. ICP and ion chromatography analyses of water column samples from Soap Lake. Fluoride, nitrate, and sulfate are ion chromatograph results. All others are ICP.

WATER COLUMN DEPTH (m)	Ba ppb	Ca ppm	Cd ppb	Cr ppb	F ppm	Fe ppm	K ppm	Mg ppm	Mn ppb
0	<40	3	<20	<20	10	0.65	600	5	<20
2	<40	4	30	20	10	<0.06	600	5	<20
4	<40	4	<20	<20	10	<0.06	500	5	<20
6	<40	3	<20	<20	10	<0.06	400	4	<20
8	<40	3	<20	<20	10	0.32	500	4	<20
10	<40	3	<20	<20	10	0.30	600	5	<20
12	<40	3	<20	<20	10	0.35	500	4	<20
14	<40	3	<20	<20	10	0.34	500	4	<20
16	<40	3	<20	<20	10	0.61	500	4	<20
18	<40	4	<20	<20	10	<0.06	500	4	<20
20	<40	4	40	<20	H	0.33	1200	5	<20
22	60	4	<20	<20	H	0.43	4100	4	30
23	60	4	<20	<20	H	0.85	4100	4	30
24	60	4	<20	<20	H	0.86	4000	5	40

H--interference from sulfate

Table 4. Continued

WATER COLUMN DEPTH (m)	Na ppm	NO(3) ppm	Si ppm	SO(4) ppm	Sr ppb	Ti ppb	Zn ppb
0	5900	<5.0	11	3000	<10	<20	<60
2	6100	5.0	11	2900	<10	<20	<60
4	5700	<5.0	11	3000	<10	50	<60
6	4700	<5.0	9	2900	<10	<20	<60
8	5300	5.0	10	3000	<10	<20	<60
10	5700	5.0	9	2900	<10	<20	<60
12	5300	<5.0	9	2900	<10	<20	<60
14	4900	<5.0	10	2900	<10	<20	<60
16	4900	<5.0	9	3000	<10	<20	<60
18	5300	5.0	11	3000	<10	<20	<60
20	12700	5.0	18	7900	10	100	<60
22	28100	<5.0	31	22000	20	210	<60
23	30200	<5.0	24	24000	20	300	<60
24	28400	<5.0	25	24000	20	340	70

H--interference from sulfate

TABLE 5. ICP and ion chromatography analyses of pore waters from Soap Lake. Fluoride, nitrate, and sulfate are ion chromatograph results. All others are ICP. Depth is in cm below sediment-water interface.

CORE	DEPTH (cm)	Ag ppb	Ba ppb	Ca ppm	Cd ppb	Cr ppb	Fe ppm	F ppm	K ppm
I	2	<60	<60	3	490	<30	0.48	10	500
I	5	<50	<50	<2	<30	<30	<0.08	10	400
I	8	<50	<50	2	30	30	0.74	10	600
I	11	340	<80	3	<40	60	1.2	10	500
I	14	<50	<50	<2	<20	30	<0.07	10	500
I	17	<50	<50	<2	*42000	40	0.80	10	600
I	20	<50	<50	<2	30	<20	<0.07	10	600
I	24	<60	<60	3	<30	<30	<0.10	10	700
I	27	<60	<60	<2	<30	50	0.55	10	600
II	2	<50	50	3	<20	30	<0.07	H	3200
II	5	<50	60	4	*4500	30	<0.08	H	3400
II	7	<40	60	3	<20	30	0.44	H	3200
II	16	220	60	3	120	30	0.85	H	3500
II	19	<40	60	3	<20	20	<0.06	H	3900
II	26	<50	60	3	<20	<20	0.93	H	3300
II	29	<50	60	3	70	30	<0.07	H	3900
II	35	<40	60	3	20	20	<0.06	H	3600
II	37	<40	60	2	<20	30	<0.07	H	3200
II	44	<40	60	2	<20	<20	<0.07	H	2900
II	46	<50	70	3	20	<20	0.48	H	3400
II	49	<50	60	2	<20	<20	0.46	H	3000
II	52	<50	70	4	<20	30	0.50	H	4000
II	59	<50	60	4	<30	<30	0.47	H	3500
II	61	<40	60	2	<20	30	0.45	H	3300
II	68	<40	60	3	<20	<20	0.43	H	3400

* Sample contaminated with cadmium acetate.

H--interference from sulfate

Table 5. Continued

CORE	DEPTH (cm)	Mg ppm	Mn ppb	Na ppm	NO(3) ppm	Si ppm	SO(4) ppm	Sr ppb	Ti ppb
I	2	<3	<30	4900	5	15	3000	<10	<30
I	5	<3	<30	4600	<5	13	3000	<10	<30
I	8	<3	<30	5900	<5	11	2700	<10	<30
I	11	<4	<40	5700	<5	18	2900	<20	<40
I	14	<2	<20	5300	5	12	3400	<10	<20
I	17	<3	<30	6400	<5	9	3400	<10	<30
I	20	<2	<20	6400	35	11	3600	20	<20
I	24	<3	<30	6900	5	14	3600	20	<30
I	27	<3	<30	6100	5	15	3800	20	<30
II	2	4	<20	27200	<5	20	21000	10	<20
II	5	4	<30	29800	<5	19	21000	10	<30
II	7	4	20	25900	<5	24	22000	10	300
II	16	4	<20	27700	<5	15	21000	10	<20
II	19	4	40	29400	<5	17	21000	10	<20
II	26	3	<20	27700	<5	21	22000	10	300
II	29	4	<20	32000	<5	18	24000	10	700
II	35	4	20	27700	<5	14	21000	10	600
II	37	3	<20	27100	<5	12	21000	20	300
II	44	3	20	25400	<5	11	23000	20	600
II	46	2	40	29000	<5	13	22000	20	600
II	49	2	30	26400	<5	12	23000	20	600
II	52	<2	40	31800	<5	14	25000	20	600
II	59	<3	30	30300	<5	11	25000	20	600
II	61	<2	30	26600	<5	11	22000	20	600
II	68	<2	20	27200	<5	13	25000	20	600

* Sample contaminated with cadmium acetate.
H--interference from sulfate

Table 5. Continued

CORE	DEPTH (cm)	Zn ppb	Zr ppb
I	2	<90	<30
I	5	<80	<30
I	8	<80	<30
I	11	<100	<40
I	14	<70	<20
I	17	<80	<30
I	20	<70	<20
I	24	<100	<30
I	27	<90	<30
II	2	<70	<20
II	5	<80	<30
II	7	<60	<20
II	16	<60	<20
II	19	<60	<20
II	26	<70	<20
II	29	120	<20
II	35	<60	<20
II	37	<70	<20
II	44	80	<20
II	46	190	<20
II	49	<70	30
II	52	<70	<20
II	59	<80	<30
II	61	<60	20
II	68	120	<20

* Sample contaminated with cadmium acetate.
H--interference from sulfate

Table 6. ICP analyses of sediments from Soap Lake. All results reported on a dry weight basis. Depth in cm below sediment-water interface.

CORE	DEPTH (cm)	Al %	Ca %	Fe %	K %	Mg %	Na %	P %	Ti %
I	2	4.3	7.5	1.9	1.2	4.2	3.4	0.11	0.21
I	5	4.2	7.0	2.3	1.5	4.8	3.3	0.08	0.25
I	8	4.6	6.5	2.6	1.6	4.7	2.8	0.07	0.28
I	11	4.4	5.9	2.8	1.8	4.8	3.2	0.07	0.29
I	14	4.2	6.5	2.7	1.8	5.4	3.4	0.07	0.27
I	17	4.0	7.5	2.2	1.8	5.0	3.0	0.07	0.24
I	20	4.8	6.3	2.5	2.0	4.7	2.9	0.07	0.27
I	24	4.7	5.8	2.4	1.9	4.7	2.9	0.06	0.27
I	27	4.6	5.8	2.4	1.9	4.6	2.8	0.06	0.26
II	2	1.9	1.2	0.92	1.7	0.66	15	0.14	0.10
II	5	2.0	1.2	0.98	1.6	0.67	15	0.14	0.10
II	7	2.2	1.3	1.0	1.7	0.70	16	0.12	0.11
II	16	2.1	1.4	1.1	1.9	0.88	16	0.13	0.12
II	*19	3.7	2.2	1.7	1.0	1.3	2.5	0.20	0.19
II	*26	3.8	2.5	1.9	1.0	1.5	2.7	0.15	0.21
II	29	2.2	1.3	1.1	1.8	0.83	15	0.12	0.12
II	*35								
II	37	1.7	1.6	1.1	1.9	1.4	15	0.10	0.12
II	*44								
II	*46	4.5	2.9	2.8	1.5	1.5	2.1	0.11	0.28
II	49	3.4	2.0	2.0	1.9	1.1	12	0.11	0.21
II	*52	5.6	2.8	3.4	1.7	1.7	2.0	0.09	0.35
II	59	4.4	1.5	2.9	2.2	1.2	9.5	0.09	0.28
II	*61	5.7	2.4	3.4	1.7	1.6	2.0	0.09	0.35
II	*68	5.7	2.3	3.9	2.0	1.5	1.9	0.09	0.37

* These samples rinsed with distilled water prior to drying.

Table 6. Continued

CORE	DEPTH (cm)	Ba ppm	Ce ppm	Co ppm	Cr ppm	Cu ppm	Ga ppm	La ppm	Li ppm
I	2	310	20	10	19	22	10	10	20
I	5	400	30	10	31	19	10	10	30
I	8	440	40	10	34	30	10	20	30
I	11	430	30	10	35	26	10	20	30
I	14	430	40	10	35	29	10	20	30
I	17	420	40	10	31	18	10	10	40
I	20	470	40	10	36	18	10	20	50
I	24	450	40	10	37	18	10	20	50
I	27	440	40	10	34	17	10	20	50
II	2	130	<10	<10	11	14	<10	<7	10
II	5	130	<10	10	12	18	<10	<7	10
II	7	130	<10	10	15	14	<10	<7	10
II	16	150	<20	10	16	19	<20	<8	10
II	*19	250	20	10	19	33	<10	10	20
II	*26	260	20	10	24	21	<20	10	20
II	29	150	<10	0	13	10	<10	<7	10
II	*35								
II	37	160	10	10	15	13	<10	<7	10
II	*44								
II	*46	350	30	10	36	40	<20	20	20
II	49	240	20	10	25	25	<10	10	20
II	*52	410	30	10	48	40	<10	20	30
II	59	300	20	10	38	28	<20	10	20
II	*61	380	40	10	44	35	<20	20	30
II	*68	400	30	10	50	28	<20	20	30

* These samples rinsed with distilled water prior to drying.

Table 6. Continued

CORE	DEPTH (cm)	Mn ppm	Mo ppm	Nd ppm	Ni ppm	Pb ppm	Sc ppm	Sr ppm	V ppm
I	2	390	<4	10	10	20	10	430	93
I	5	520	<4	10	20	20	10	390	110
I	8	570	<4	20	20	20	10	380	110
I	11	580	<4	20	20	10	10	350	110
I	14	580	<4	20	20	10	10	370	120
I	17	500	<4	20	20	10	10	420	110
I	20	500	<4	20	20	<8	10	380	120
I	24	480	<4	20	20	<8	10	350	120
I	27	470	4	20	20	10	10	350	110
II	2	160	<7	<10	10	<10	<7	110	22
II	5	160	<7	<10	10	<10	<7	110	22
II	7	170	<7	<10	<7	<10	<7	120	23
II	16	180	<8	<20	<8	<20	<8	120	27
II	*19	300	<6	<10	10	20	<6	200	52
II	*26	330	<8	<20	10	<20	<8	220	53
II	29	180	<7	<10	10	<10	<7	120	29
II	*35								
II	37	200	<7	<10	10	<10	<7	110	37
II	*44								
II	*46	470	8	20	20	20	10	220	62
II	49	340	<7	<10	10	20	<7	160	44
II	*52	570	<7	<10	20	20	10	240	72
II	59	440	9	<20	20	<20	10	140	54
II	*61	550	<8	<20	20	20	10	230	70
II	*68	570	16	<20	20	<20	10	190	77

* These samples rinsed with distilled water prior to drying.

Table 6. Continued

CORE	DEPTH (cm)	Y ppm	Zn ppm
I	2	10	31
I	5	10	39
I	8	20	47
I	11	10	46
I	14	10	46
I	17	10	30
I	20	10	36
I	24	10	34
I	27	10	34
II	2	<7	28
II	5	<7	34
II	7	<7	24
II	16	<8	32
II	*19	10	49
II	*26	<8	45
II	29	<7	26
II	*35		
II	37	<7	29
II	*44		
II	*46	10	76
II	49	<7	48
II	*52	10	80
II	59	<8	68
II	*61	10	78
II	*68	10	80

* These samples rinsed with distilled water prior to drying.

Table 7. ICP analyses of water column, pore water, and sediment samples from Soap Lake whose element values were less than the detection limit for all samples.

ELEMENT	WATER COLUMN ppb	PORE WATER CORE I ppb	PORE WATER CORE II ppb	SEDIMENT CORE I ppm	SEDIMENT CORE II ppm
Ag	<40			<4	<8
Al	<2	<4	<3		
As				<20	<40
Au				<20	<30
B	<200	<400	<300		
Be	<20	<40	<30	<2	<4
Bi	<200	<400	<300	<20	<40
Cd				<4	<8
Co	<60	<100	<80		
Cu	<200	<400	<300		
Eu				<4	<8
Ga	<100	<200	<100		
Ho				<8	<20
Li	<800	<1600	<1000		
Mo	<200	<400	<300		
Nb				<8	<20
Ni	<100	<200	<100		
Pb	<200	<400	<300		
Sn	<100	<200	<200	<20	<40
Ta				<80	<200
Th				<8	<20
U				<200	<400
V	<100	<200	<200		
Yb				<2	<4
Zr	<20				