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Chemistry of Lake Tahoe, California-Nevada, and nearby springs

by

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ABSTRACT

The chemistry of springs in the Lake Tahoe area is used to study the process of weathering and the processes that determine the major-element chemistry of the lake. The chemistry of cold springs is divided into groups based on chemical patterns in modified Schoeller plots. The chemistry of these groups is modeled using reactions of various minerals with dissolved carbon dioxide to produce major elements in solution and residual clay. The modeled compositions are a good match to measured compositions except at higher concentrations of bicarbonate, where concentrations of dissolved constituents are probably limited by saturation. The available data indicate that the chemistry of streams is basically a conservative combination of spring chemistry. The chemistry of the lake can be explained by a steady state model involving input from stream inflow plus direct precipitation and discharge from outflow plus evaporation. The silica balance of the lake requires a loss term from diatoms, and there is a suggestion of exchange of calcium for magnesium. Deeply circulating waters in two thermal springs in the area have concentrations of chloride and sulfate higher than in cold springs that have weathering as the basic process driving their chemistry.

INTRODUCTION

Lake Tahoe and its nearby cold springs provide a useful background for studying the chemistry of Crater Lake, Oregon (Nathenson and Thompson, 1989; Nathenson, 1989). Lake Tahoe is a deep, cold lake at high altitude with a limited drainage basin in an area of relatively uniform geology. Crater Lake is also a deep, cold lake at high altitude with a limited drainage basin. Major differences are that Lake Tahoe is in a crystalline granitic terrain whereas Crater Lake is an area of glassy volcanic rocks. By studying the Tahoe area, the techniques used can then be applied to the Crater Lake area to focus on the questions of weathering (Nathenson and Thompson, 1989) and of input of additional constituents into Crater Lake beyond that in precipitation and runoff (Nathenson, 1989). Simpson (1970) used the same comparison to study the same set of questions.

Lake Tahoe has had numerous limnological studies because of the questions concerning the effects on the lake of development on the shore (summarized in Goldman, 1981). In addition, Feth and others (1964) obtained a significant amount of data in the Tahoe area as part of their larger study of the process of weathering in the Sierra Nevada. By combining these data sets and interpretations, it is possible to study a number of questions in the Tahoe area: 1) How does the process of weathering of rock result in the chemical composition of cold-spring waters? 2) How does the combination of these cold spring compositions result in the chemistry of streams that feed Lake Tahoe? 3) Using the hydrologic balance for Lake Tahoe, what is the fate of these dissolved constituents in the lake?

SPRING CHEMISTRY AS A RESULT OF ROCK WEATHERING

Feth and others (1964) carefully sampled and analyzed the chemistry of numerous cold springs in the Sierra Nevada. The locations of these springs in the Tahoe area are shown in Figure 1 along with the drainage basin for the lake. Some of the samples are outside of the drainage basin, but they are above the lake in altitude and can still be used to study the process of weathering to produce spring compositions of relevance to the Tahoe basin. Figure 2 shows a plot of specific conductance of the cold-spring samples versus the concentrations of anions and cations. The close agreement between the anions and cations and the systematic increase in conductivity with concentration demonstrates the high quality of the analytical work. Based on physical observations of the springs, Feth and others (1964) divided the springs into: ephemeral springs, perennial springs in quartz monzonite, granodiorite, or undifferentiated granitic rocks, and thermal springs. The present study proposes a slightly different division based on chemical type as determined by plots on modified Schoeller diagrams (e.g. Hem, 1985, p. 177). Figure 3 shows a simplified version of a Schoeller diagram where calcium and magnesium and sodium and potassium are combined because of their similar chemical affinity. Chloride and sulfate are left off because of the small concentrations in these samples relative to other constituents. The purpose of Figure 3 is to show that the samples naturally divide into three groups (plus thermal and mixed waters to be discussed below). The group with the lowest concentrations has the four constituents all increasing basically together. The middle group is dominated by calcium plus magnesium and bicarbonate. The silica concentrations in this group systematically increase with bicarbonate concentration. The third group has nearly constant sodium plus potassium with a large range of calcium plus magnesium and bicarbonate. Silica concentrations are either constant or show a tendency to systematically decrease with increasing bicarbonate concentrations. Based on Figure 3, the analyses of the cold waters have been divided into three groups, and the data are reported this way in Table 2. Group I has 6 of Feth and others' ephemeral springs and one perennial spring in granodiorite. Group II has two ephemeral springs and two perennial springs. Group III has 5 perennial springs. The net result then is a somewhat finer division of the springs based on chemistry and a recognition that ephemeral and perennial springs may have virtually identical chemistries.

Figures 4 and 5 show the data for Groups I, II, and III with all the concentrations shown individually on modified Schoeller plots. The ionic species are plotted in milliequivalents per liter, so that relative proportions of constituents will correspond to those in a Piper diagram (e.g. Hem, 1985, p. 179). Silica is shown in millimoles per liter, because it is not an ionic species. For singly charged species, the value of the concentration in milliequivalents is the same as the value in millimoles; while for doubly charged species, the concentration in milliequivalents is twice that of the value in millimoles.

The concentrations in the Group I analyses are so low (Figure 4) that some of the small differences for that group probably are not real. The three plots (Figures 4 and 5) show that each group has a reasonable chemical affinity, and one is justified in calculating the averages shown in Table 2. Certainly, the three groups show a stronger similarity to each other than they do to members of another group. In both groups II and III, there appears to be a variable relationship between the relative amounts of calcium and magnesium. Groups I and II show an increasing concentration of silica as bicarbonate increases. Group III shows a slightly decreasing concentration of silica as bicarbonate increases and has lower silica concentrations than Group II even though the bicarbonate concentrations are higher.

The explanation for the concentrations of constituents in water in these spring samples is that carbon dioxide from the atmosphere and from the soil zone dissolves in water (Feth and others, 1964). The most important source of carbon dioxide is proposed to be the soil zone where concentrations can be many times that in the atmosphere (e.g. Solomon and Cerling, 1987). The carbon dioxide forms an acid solution in water and reacts with minerals in the rock to produce silica, bicarbonate, and major ions in solution and a residual clay. Garrels and MacKenzie (1967) extended the work of Feth and others (1964) by proposing specific reactions for the various constituents. The four reactions proposed by Garrels and MacKenzie are:

Biotite Kaolinite

$$\mathrm{KMg_3AlSi_3O_{10}(OH)_2} + 7\ \mathrm{CO_2} + \frac{7}{2}\ \mathrm{H_2O} = \frac{1}{2}\ \mathrm{Al_2Si_2O_5(OH)_4} + \mathrm{K^+} + 6 \times \frac{1}{2}\ \mathrm{Mg^{+2}} + 7\ \mathrm{HCO_3^-} + 2\ \mathrm{SiO_2} \tag{1}$$

Plagioclase Kaolinite

$$\mathrm{Na_{0.62}Ca_{0.38}Al_{1.38}Si_{2.62}O_8} + 1.37\ \mathrm{CO_2} + 2.06\ \mathrm{H_2O} = 0.69\ \mathrm{Al_2Si_2O_5(OH)_4} + 0.62\ \mathrm{Na^+} + 0.76 \times \frac{1}{2}\ \mathrm{Ca^{+2}} + 1.24\ \mathrm{SiO_2} + 1.37\ \mathrm{HCO_3^-} \tag{2}$$

Plagioclase Montmorillonite

$$\mathrm{Na_{0.62}Ca_{0.38}Al_{1.38}Si_{2.62}O_8} + 1.18\ \mathrm{CO_2} + 1.18\ \mathrm{H_2O} = 0.59\ \mathrm{Ca_{0.17}Al_{2.33}Si_{3.67}O_{10}(OH)_2} + 0.62\ \mathrm{Na^+} + 0.56 \times \frac{1}{2}\ \mathrm{Ca^{+2}} + 0.45\ \mathrm{SiO_2} + 1.18\ \mathrm{HCO_3^-} \tag{3}$$

K-feldspar Kaolinite

$$\mathrm{KAlSi_3O_8} + \mathrm{CO_2} + 1.5\ \mathrm{H_2O} = \frac{1}{2}\ \mathrm{Al_2Si_2O_5(OH)_4} + \mathrm{K^+} + \mathrm{HCO_3^-} + 2\ \mathrm{SiO_2}. \tag{4}$$

The reactions are written with a factor of 1/2 in front of the doubly charged species so that calculations in milliequivalents may easily be done.

Table 3 presents calculations using these reactions to produce the average composition of the three waters. The concentrations of sulfate and chloride in the water are proposed to come from precipitation. The concentrations measured in Sierra precipitation are doubled in Table 3, because Crippen and Pavelka (1970) found that precipitation on land in the Lake Tahoe area evaporates about half its volume during the process of runoff. The coefficients for each reaction in Table 3 are chosen by matching a particular species. For Group I waters, the coefficient of the plagioclase to kaolinite reaction is based on the remaining Na, and the coefficient for the K-feldspar to kaolinite reaction is based on the remaining K after the concentrations in precipitation are subtracted. The calculation for Group II waters requires adding the biotite to kaolinite reaction to match the Mg. The calculation for Group III waters does not need the K-feldspar to kaolinite reaction, because all the K is supplied by the biotite to kaolinite reaction.

The modeled compositions of the average of Group I and II waters are reasonably close to the actual compositions. The average composition of Group I waters is 0.034 meq/L lower in anions than in cations. If this concentration were added to the bicarbonate concentration, the agreement between modeled and actual composition would be closer. The chloride and sulfate in Sierra precipitation is higher than that in the average of Group II waters; this probably reflects analytical uncertainty in these two constituents or, less likely, a loss as the water circulates in the subsurface. The modeled composition of Group III waters is not able to produce the correct calcium or bicarbonate concentration. If calcite were a primary mineral, the residual calcium and bicarbonate could be from dissolving that mineral; however, calcite is not a primary mineral in granitic rocks. The appearance of the plots of water composition in Figure 4 compared to Figure 5 suggests that Group III waters are not just a dissolution of minerals with all constituents staying in solution, but that some constituents are limited by solubility considerations. The solubility of quartz, chalcedony, α-cristobalite, β-cristobalite, and amorphous silica at the mean annual air temperature of 6°C are about 0.05, 0.17, 0.27, 0.87, 1.33 mmol/L (Fournier, 1981) compared to the average concentration of 0.35 mmol/L in Group III waters. Although it is possible that one of the silica phases is limiting the solubility in these waters, the decreasing silica concentration with increasing bicarbonate concentration suggests that it may be caused by a reaction involving major-ion concentrations.

To understand the pattern of reaction of the various waters as concentrations change, we can plot one constituent against another. Figure 6 shows the sum of Ca+Mg versus bicarbonate in meq/L. The two lines shown are for 1:1 and 0.5:1 ratios in milliequivalents of Ca+Mg:HCO_3. As most of the Ca or Mg and HCO_3 is brought into solution either by the reaction of plagioclase to kaolinite (with a 0.55:1 ratio), biotite to kaolinite (with a 0.86:1 ratio), or plagioclase to montmorillonite (with a 0.47:1 ratio), it is reassuring that essentially all the points lie between the limits shown.

Figure 7 shows silica versus sodium concentration. For Groups I and II waters, the calculations in Table 3 show that most of the silica is brought into solution by the reaction of plagioclase to kaolinite. The ratio SiO_2:Na for this reaction is 2:1, which is shown on Figure 7, and the compositions of Group I and II waters agree with this ratio. The silica in Group III waters comes from a more complex set of reactions than that used in Table 3, and the data shown on Figure 7 show a different trend than the data for waters of Groups I and II.

Figure 8 shows silica versus bicarbonate. Most of the silica and bicarbonate in Groups I and II waters are contributed by the reaction of plagioclase to kaolinite with a slope of 0.9. The data are in reasonable agreement with this slope. The Group III waters show a trend of decreasing silica concentration with increasing bicarbonate concentration. Garrels (1967) proposed that at higher levels of bicarbonate, the equilibrium of kaolinite and montmorillonite should become important in limiting silica concentrations. His specific reaction involved the conversion of kaolinite to a calcium montmorillonite. Based on the increasing concentrations of calcium with bicarbonate (Figure 6) and the near constancy of sodium concentrations in Group III waters (Table 2), it seems likely that the reaction here should involve a sodium montmorillonite.

CHEMISTRY OF MIXED WATER AND THERMAL SPRINGS

In plotting the chemistry of the cold springs in the modified Schoeller diagrams, it became clear that sample 1170 was anomalous compared to all other cold waters. Figure 9 shows the data for sample 1170 along with those for Meyers Warm Spring (1219T) and cold-water sample 1571. All these springs are in the same area (Figure 1). Sample 1170 is anomalously high compared to the cold water in concentrations of sodium, chloride, and sulfate. Values for constituents for sample 1170 are about one third between the values for Meyers Warm Spring and the cold water, and it is likely that sample 1170 represents a mixture of these two waters. Because Feth and others (1964) included it as one of their perennial springs, recognition that it is a mixed water removes a sample that is difficult to explain in the context of weathering.

The measured temperature in Meyers Warm Spring is 24°C. The Na-K-Ca geothermometer temperature is 53°C, and the quartz and chalcedony temperatures are 67° and 35°C, respectively (Fournier, 1981). A reasonable estimate of subsurface temperature based on these geothermometer temperatures is about 40°C, which is roughly in agreement with what the measured spring temperature would be if there were significant conductive cooling as the water rose to the surface. Heat flow in Lake Tahoe is 67 mW/m^2, which is transitional between the low values in the Sierra Nevada and the high values in the Basin and Range (Henyey and Lee, 1976). Using a representative value for the thermal conductivity of granite of 3.6 W/m °C, the temperature gradient would be 19°C/km. Thus, the 24°C measured temperature requires a circulation depth of about 1 km, and the geothermometer temperature requires a circulation depth of 1.8 km. Meyers Warm Spring possesses the chemical characteristics usually associated with thermal springs of anomalous concentrations of choride compared to cold waters and very little magnesium. The concentration of sulfate in Meyers Warm Spring is anomalous compared to cold waters, but it is not necessarily indicative of a thermal spring. Feth and others (1964) discuss various explanations for the sources of chloride and sulfate in a water such as that found in Meyers Warm Spring.

The data for Brockway Hot Springs and Meyers Warm Spring are shown in Figure 10. The concentrations of sodium, chloride, and sulfate in Brockway Hot Springs are quite high compared to the cold springs and Meyers Warm Spring. The measured temperature is 55°C, and the Na-K-Ca and chalcedony temperatures are 94° and 90°C, respectively. Mariner and others (1977) picked 94°C as the best estimate of subsurface temperature, requiring a depth of circulation of 4.6 km. Because of the large size of Lake Tahoe and its drainage basin, it seems unlikely that the flow from Brockway Hot Springs could have much affect on the chemistry of the lake; however, its location on the shore of the lake indicates that some of the variability of heat flows measured in the sediments of Lake Tahoe by Henyey and Lee (1976) could be caused by hydrothermal circulation.

In addition, Glen Alpine Springs consist of several cold (8°C) soda springs that discharge in the Tahoe basin. The soda spring waters are high in calcium, magnesium, sodium, bicarbonate, and chloride concentrations (Table 2). The basic chemistry results from the dissolution of rock by water having high concentrations of dissolved carbon dioxide. The source of the carbon dioxide appears to be quite deep, and chemical and isotopic data indicate that the water was probably in contact with granite and metamorphosed marine sedimentary rocks (Barnes and others, 1981). Soda springs are relatively common in the Sierra Nevada (Barnes and others, 1981) indicating good communication with sources of carbon dioxide at depth.

CHEMISTRY OF STREAMS AND THE LAKE

In order to understand the chemistry of major constituents in Lake Tahoe, it would be best if there were a complete set of analyses of all the streams entering the lake, so that a flow source-term could be calculated. Unfortunately, there seem to be few complete chemical analyses for streams entering the lake. Table 2 gives analyses for the Upper Truckee River, which contributes about 19 % of the stream inflow to Lake Tahoe, and for Watson Creek. Figure 11 compares these analyses to the averages for groups I, II, and III waters. In general, the two streams have chemistry that is similar to the chemistry of groups I and II or a mixture of them. There is a suggestion that calcium is being exchanged for magnesium as spring water flows in streams, but the differences are small enough that they may not be significant. Assuming that the samples from these two streams are representative of the range of compositions to be encountered in the streams feeding Lake Tahoe, we can use the data as part of a chemical balance for the lake.

The hydrologic balance can be used to develop a model showing how the concentrations of dissolved constituents in the lake should relate to the various inputs and the discharge. The surrounding drainage area adds water through stream flow at a rate q_i with a composition c_i. Precipitation at a rate q_p with a dissolved concentration of c_p falls on the lake. The inflow is balanced by evaporation q_e, which is assumed to carry no constituents, and by discharge q_d which has the same concentration as that in the entire lake c. The lake mixes to total depth only in some years, but to depths of 200 m every year (Goldman, 1981), so that the assumption that the outflow has the same composition as the lake water is reasonable. The hydrologic balance is:

$$q_i + q_p = q_e + q_d, \qquad (5)$$

and the chemical balance is:

$$q_i\, c_i + q_p\, c_p = q_d\, c. \qquad (6)$$

All the flows q are given in Table 1. The concentrations in precipitation and the lake are given in Table 2. As the concentration in the inflow is the least well known, I will use equation (6) to calculate it. Figure 12 (top) shows the calculated concentration c_i along with the measured values for the Upper Truckee River and Watson Creek samples. Except for magnesium and silica, the calculated inflow is approximately a combination of these representative samples. Figure 12 (bottom) and Table 4 compare a mixture of 60 % water with chemistry like that from the Upper Truckee River with 40 % Watson Creek type water to the calculated inflow. The relative percentages were chosen to match the bicarbonate concentration. The agreement is quite good except for magnesium and silica. The difference in magnesium may indicate that there is continued exchange of calcium for magnesium with rock or sediments as the water ages in the lake, although more data would be necessary to confirm this. The calculated inflow concentration c_i is much lower in silica than the mixture would indicate, and this difference can be explained by considering the amount of silica that is deposited in the sediments of Lake Tahoe by diatoms.

From Table 4, the silica concentration in the mixture of Upper Truckee River water and Watson Creek water is 19.4 mg/L. The calculated inflow concentration from the measured silica in the lake is 7.6 mg/L. The difference of 12 mg/L is the silica that is being consumed by diatoms. Using the inflow value from Table 1, the calculated loss rate is 4.6 X 10^{12}mg/y. Hyne and others (1972) estimated for core 10 that 30 cm of sediment overlay the top layer of sediments that was dated at 2,060 years before present (bp) for a recent sedimentation rate of 0.15 mm/yr for deep layers. The upper 100 cm of sediment was deposited between 2000 years bp and about 7000 years bp, for a sedimentation rate of 0.2 mm/yr. Most of the sediment samples obtained at Lake Tahoe can be characterized as pollen-rich diatomaceous ooze with 50 % to 90 % diatoms and pollen (Court and others, 1972). This organic ooze is not found in all parts of the lake floor, so that some part of the area of the lake does not have a significant amount of diatom deposition. For the size diatoms in Lake Tahoe (Goldman, 1981), the density of silica per volume of diatom is 0.25 g/cm^3 based on the correlation in Conley and others (1987). Assuming that diatoms are 50 % of the core and that substantial amounts of diatoms are deposited over only one half the lake area, the calculated deposition rate is 4.6 X 10^{12} mg/y, the same as the value calculated above. Considering all the uncertainties in both calculations, this should be considered an order of magnitude calculation, and the excellent agreement is fortuitous. The calculation shows that the one constituent that is clearly being lost from the lake into the sediments can be accounted for. It is possible that other constituents also involve some losses, but the data available indicate that the other constituents are approximately conserved with neither a source nor a sink in the sediment process.

The amount of silica lost can be compared to the average annual biomass to get an idea of the fraction lost per year. Dividing the loss per year of 4.6 X 10^{12} mg/y by the lake volume gives a loss of 31 µg/L y. The annual average biomass (which is more than just diatoms) in 1969 was 83 µg/L (Goldman, 1981), so that 37 % of the average annual biomass is lost to the sediments each year. By 1979, the annual average biomass had doubled to 167 µg/L. Although the amount of silica lost is a significant fraction of the biomass, the average annual biomass is a small fraction of the total available silica in the lake.

CONCLUSIONS AND DISCUSSION

The major conclusions of this study reaffirm those of earlier investigators with minor modifications. The major element compositions of cold spring waters are driven by the solution of carbon dioxide in precipitation and subsequent weathering of minerals in rock (Feth and others, 1964; Garrels and MacKenzie, 1967). The division of cold springs into ephemeral and perennial of Feth and others (1964) has been modified to a division based on chemical patterns. Group I springs correspond to their ephemeral classification, Group III to their perennial classification, and Group II has springs of both groups. By showing that the sample from spring 1170 is a mixture of thermal and cold water, the concentrations of sulfate and chloride in this sample are no longer an unexplained anomaly in the group of perennial springs. Although not compelling, the available data indicate that the chemistry of streams is basically a conservative combination of spring chemistry. The chemistry of the lake can be explained by a steady state model involving input from stream inflow plus direct precipitation and discharge from outflow plus evaporation (Friedman and others, 1964; Simpson, 1970). The silica balance requires a loss term from diatoms, and there is a suggestion of exchange of calcium for magnesium.

Deeply circulating waters such as those at Meyers Warm Spring and Brockway Hot Springs are able to pick up concentrations of chloride and sulfate that do not appear in springs that have weathering as the basic process producing their chemical composition. Possible sources of chloride and sulfate are attack on fluid inclusions, replacement of atoms in the lattices of minerals, or the addition of nonmeteoric water (Feth and others, 1964). An additional possibility for a spring such as Brockway Hot Springs that circulates very deeply is that the water contacts rocks that are not exposed at the surface. All these mechanisms are possible, but the available data do not provide much of an indication of what the process actually is.

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Table 1. Physical characteristics of Lake Tahoe (Crippen and Pavelka, 1970).

Surface elevation		1897 m
Greatest measured depth		501 m
Average water depth		305 m
Volume		150 km^3
Surface area		495 km^2
Area of watershed (not including lake)		816 km^2
Water balance	(flow per year divided by lake area):	
Inflow	q_i	0.78 m/y
Direct precipitation	q_p	0.53 m/y
Evaporation	q_e	0.88 m/y
Discharge	q_d	0.43 m/y

Table 2. Chemical Analyses of waters in the Vicinity of Lake Tahoe

Sample Numbers[a]	Name or Locality	Date	1 pH	SiO_2	Ca	Mg	Na	K	HCO_3	SO_4	Cl	F	Cond. (µmhos)	Water T. °C
				in mg/L										
Group I springs														
1222 E	NE1/4,S31,T12N,R18E	5/ 3/60	5.7	13	1.6	0.5	2.4	1.5	12	3.6	0.5	0.1	28	3
1499 E	NW1/4,S30,T17N,R19E	5/30/61	5.5	10	3.4	0.0	2.9	1.8	14	0.0	2.0	--	30	--
1500 E	do	5/30/61	5.3	11	2.2	0.0	2.9	2.1	11	3.0	1.8	--	29	6
1502 E	do	5/30/61	6.4	13	1.8	0.6	2.3	0.3	12	0.0	0.1	--	19	--
1504 E	NW1/4,S30,T17N,R19E	5/30/61	5.7	13	1.4	0.2	2.5	0.3	9	0.0	0.6	--	17	7
1506 E	NW1/4,S12,T11N,R17E	5/31/61	5.6	8.1	1.3	0.4	1.3	0.3	7	0.0	0.2	--	12	--
1573 G	NW1/4,S28,T13N,R17E	10/18/61	6.5	15	2.8	0.1	2.2	1.4	13	1.6	0.2	0.1	31	7
	Mean concentration			12	2.1	0.3	2.4	1.1	11	1.2	0.8			
Group II springs														
1132 E	NE1/4,S 6,T14N,R19E	10/19/59	7.5	28	5.6	2.9	4.6	2.5	41	2.0	0.1	0.1	67	4
1226 E	SW1/4,S32,T15N,R19E	5/ 4/60	6.9	37	4.9	1.1	6.3	2.1	42	0.6	0.2	0.2	68	11
1569 QM	NE1/4,S32,T12N,R18E	10/17/61	6.3	29	7.0	0.6	5.5	1.6	40	0.0	0.2	0.0	65	5
1574 G	NE1/4,S21,T13N,R17E	10/18/61	6.8	23	6.5	0.8	3.9	1.7	37	0.0	0.2	0.1	59	7
	Mean concentration			29	6.0	1.3	5.1	2.0	40	0.7	0.2			
Group III springs														
1131 QM	Monitor Spring SE1/4,S32,T15N,R19E	10/19/59	7.1	23	11	4.9	5.4	2.6	67	1.8	0.4	0.0	110	10
1571 QM	N Center S32,T12N,R18E	10/17/61	7.4	24	12	0.8	6.4	2.3	63	1.6	0.3	0.1	102	9
1172 G	Stambaugh Spring SW1/4,S34,T14N,R18E	12/12/59	6.8	20	16	6.3	7.0	2.5	105	1.2	0.5	0.1	163	8
1171 UG	Folsom Spring SW1/4,S23,T13N,R18E	12/12/59	7.3	21	16	2.3	8.2	2.2	84	3.3	0.7	0.1	135	8
1331 UG	SW1/4,S 6,T14N,R19E	9/20/60	7.4	16	18	6.1	5.2	1.4	105	1.0	0.3	0.1	164	9
	Mean concentration			21	15	4.1	6.4	2.2	85	1.8	0.4			
Thermal, mixed, and soda springs														
1219	Meyers Warm Spring		9.4f	22	2.8	0.0	33	0.9	47	13	14	0.5		24
1170 G	NW1/4,S5,T11N,R18E	12/11/59	7.1	27	8.8	0.6	15	2.3	55	9.9	6.0	0.2	121	9
----	Brockway Hot Springs NE1/4,S30,T16N,R18E	74	8.7	71	4.4	0.2	110	3.0	84	34	100	2.9		55
----	Glen Alpine Springs		6.0	45	275	54	350	9.5	1140	10	550			8
Snow, Lake Tahoe, and streams														
----	Sierra Snow			0.16	0.40	0.17	0.46	0.32	2.88	0.95	0.50			
----	Lake Tahoe	74	8.1	13	8.4	2.4	6.6	1.8	51	<1	2.4	<.1		19
3070-5	Lake Tahoe			14	9	4.4	6.2	1.8	52	2.4	2.2	0.2		
3046-8	Upper Truckee River			13	3.2	1.2	2.3	0.3	16	0	0.9	0.1		
3043-14	Watson Creek			29	8.0	1.9	3.4	1.2	44	0.9	0.8	0.1		

Chemical analyses from Feth and others (1964) except for Lake Tahoe and Brockway Hot Springs from Mariner and others (1977), Glen Alpine Springs from Barnes and others (1981), and samples for Lake Tahoe, Upper Truckee River, and Watson Creek from Friedman and others (1964).

[a] Letter after 1000 series sample numbers denotes the groupings of Feth and others (1964); E, ephemeral springs, QM, perennial springs in quartz monzonite, G, perennial springs in granodiorite, UG, perennial springs in undifferentiated granitic rocks.

Table 3. Calculation of water compositions (in meq/L for dissolved ions and mmol/L for silica) based on reactions (1) to (4).

	Ca	Mg	Na	K	Cl	SO_4	HCO_3	SiO_2
Group I average	0.105	0.025	0.104	0.028	0.023	0.025	0.180	0.200
2 x Sierra Precipitation	0.040	0.028	0.040	0.016	0.028	0.040	0.094	0.006
0.1 x Plagioclase to kaolinite	0.076		0.062				0.137	0.124
0.012 x K-feldspar to kaolinite				0.012			0.012	0.024
Calculated water composition	0.116	0.028	0.102	0.028	0.028	0.040	0.243	0.154
Group II average	0.299	0.107	0.222	0.051	0.006	0.015	0.656	0.483
2 x Sierra Precipitation	0.040	0.028	0.040	0.016	0.028	0.040	0.094	0.006
0.32 x Plagioclase to kaolinite	0.243		0.198				0.438	0.397
0.02 x K-feldspar to kaolinite				0.020			0.020	0.040
0.0133 x Biotite to kaolinite		0.080		0.013			0.093	0.027
Calculated water composition	0.283	0.108	0.238	0.049	0.028	0.040	0.645	0.470
Group III average	0.749	0.337	0.278	0.056	0.011	0.037	1.393	0.349
2 x Sierra Precipitation	0.040	0.028	0.040	0.016	0.028	0.040	0.094	0.006
0.1 x Plagioclase to kaolinite	0.076		0.062				0.137	0.124
0.05 x Biotite to kaolinite		0.300		0.050			0.350	0.100
0.3 x Plagioclase to montmorillonite	0.168		0.186				0.354	0.135
Calculated water composition	0.284	0.328	0.288	0.066	0.028	0.040	0.935	0.365
Residual Ca and HCO_3	0.465						0.458	

Table 4. Calculated compositions. See text for explanation.

	SiO_2	Ca	Mg	Na	K	HCO_3	SO_4	Cl
	in mg/L							
Calculated composition of the inflow to Lake Tahoe	7.6	4.7	2.3	3.1	0.8	27	0.7	0.9
Mixture of 60 % Upper Truckee River water and 40 % Watson Creek water	19.4	5.1	1.5	2.7	0.7	27	0.4	0.9

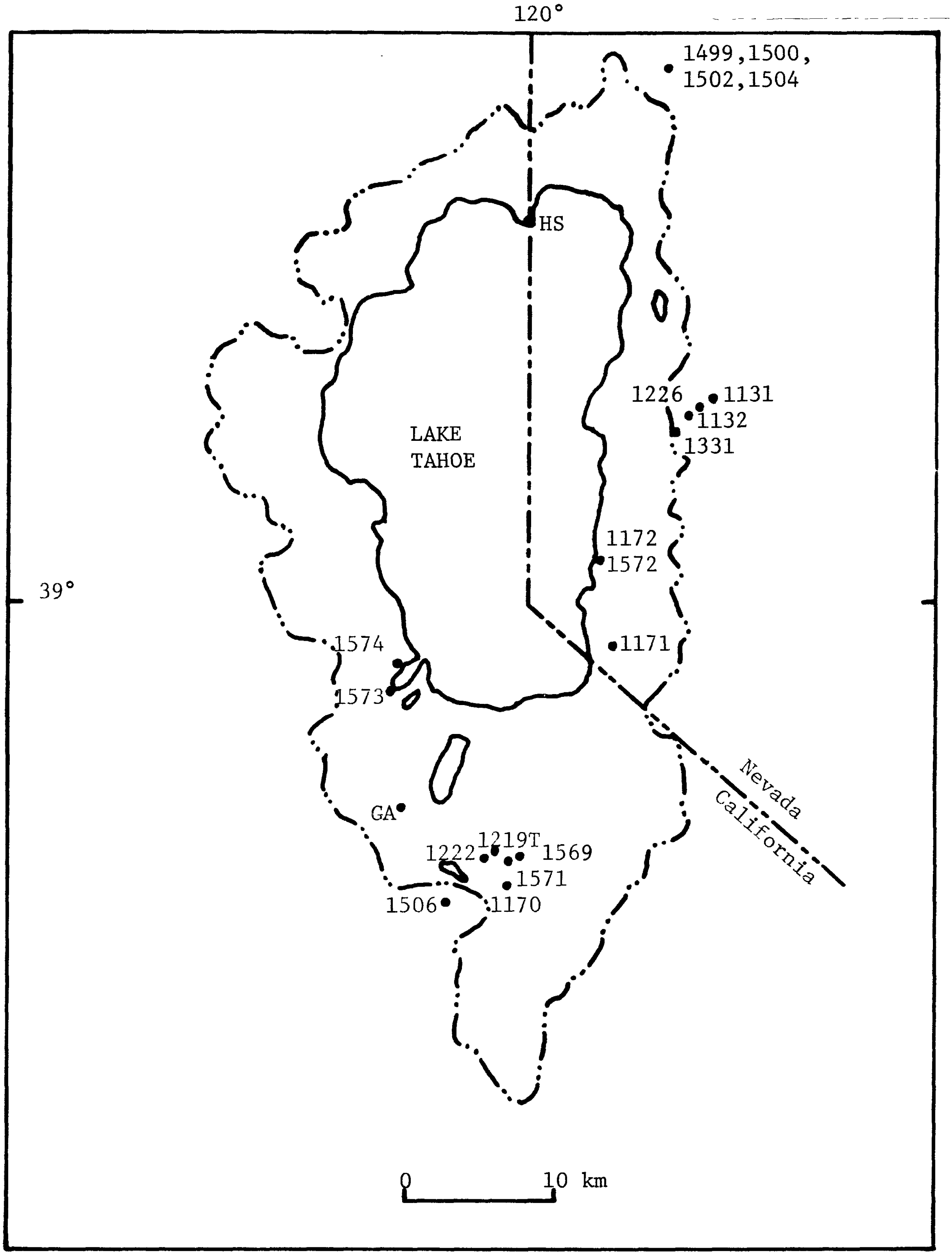

Figure 1. Map of Lake Tahoe showing drainage basin and locations for samples given in Table 2. HS is Brockway Hot Springs and GA is Glen Alpine Springs. Samples outside of drainage basin are at an elevation that is higher than the surface of Lake Tahoe.

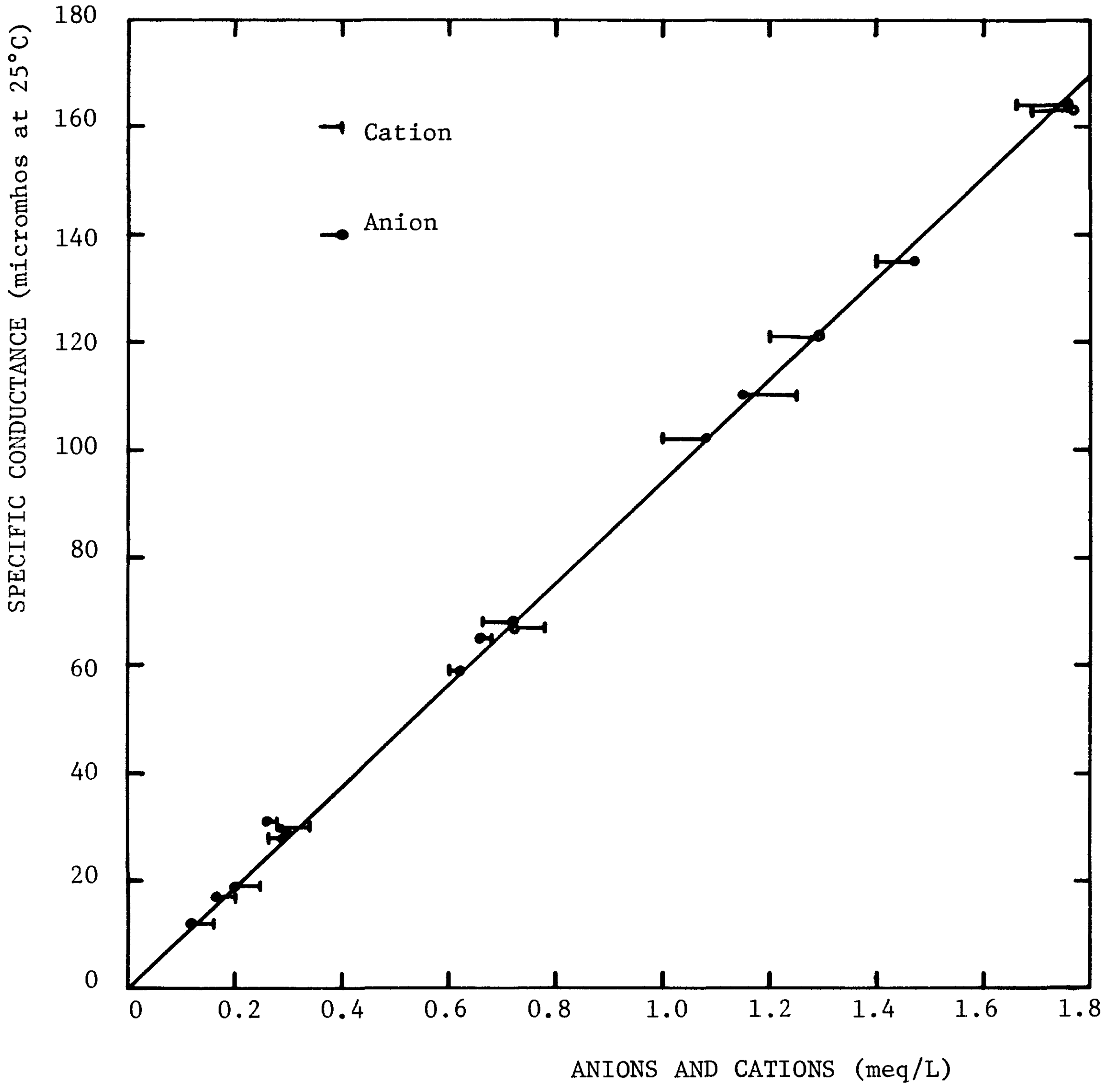

Figure 2. Specific conductance versus concentration of anions and cations in milliequivalents per liter (meq/L).

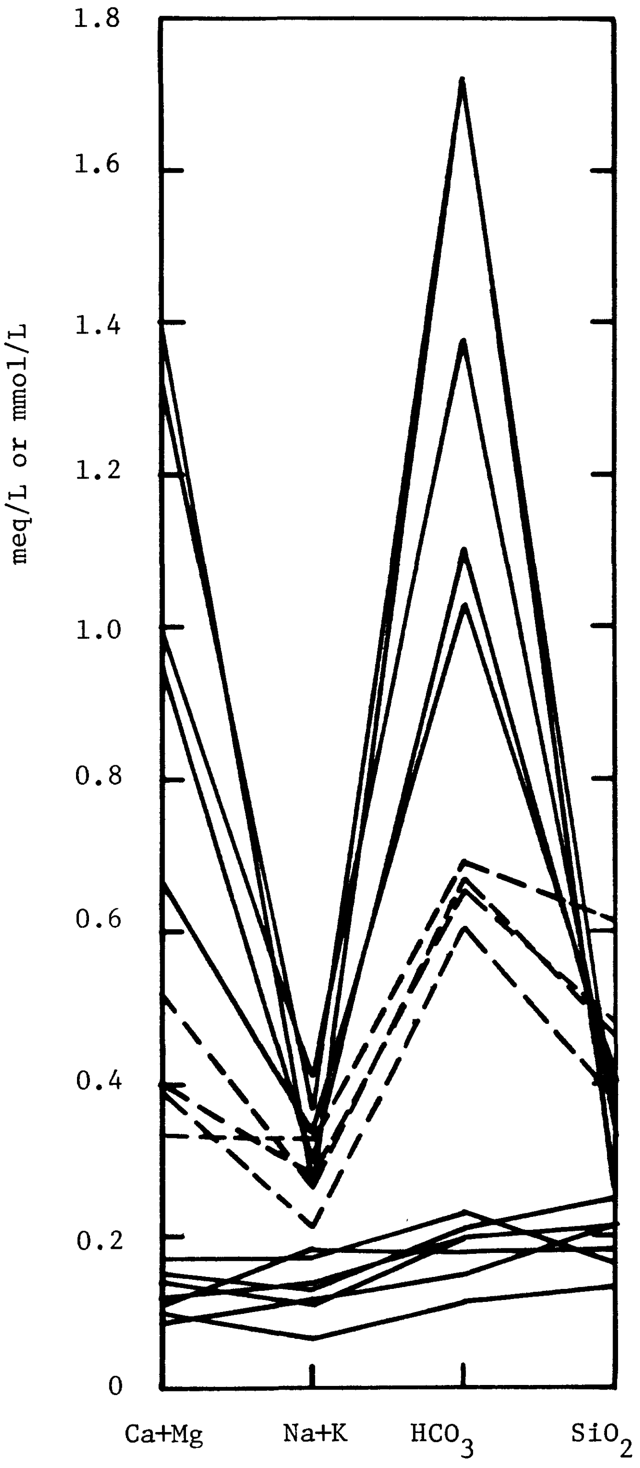

Figure 3. Modified Schoeller plot of waters in Groups I, II, and III in Table 2. Chloride and sulfate have been left off, and cations have been grouped as in a Piper diagram (Hem, 1970). Group I samples are solid lines at bottom, Group II are broken lines in the middle, and Group III waters are solid lines in the top of the figure. Ionic species are in meq/L, and silica is in millimoles per liter (mmol/L).

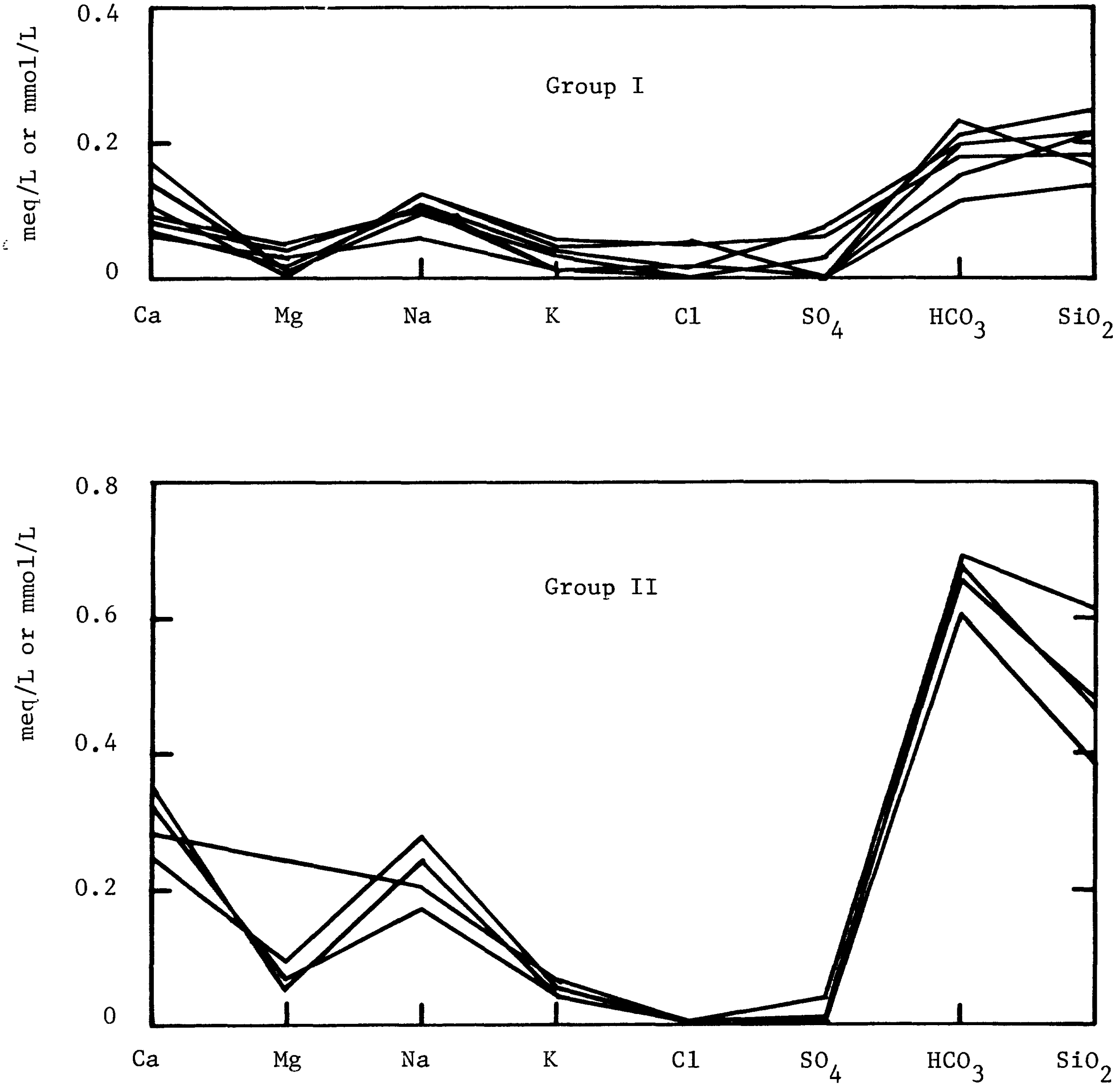

Figure 4. Modified Schoeller plot for water samples in Groups I and II. Ionic species are in meq/L, and silica is in mmol/L.

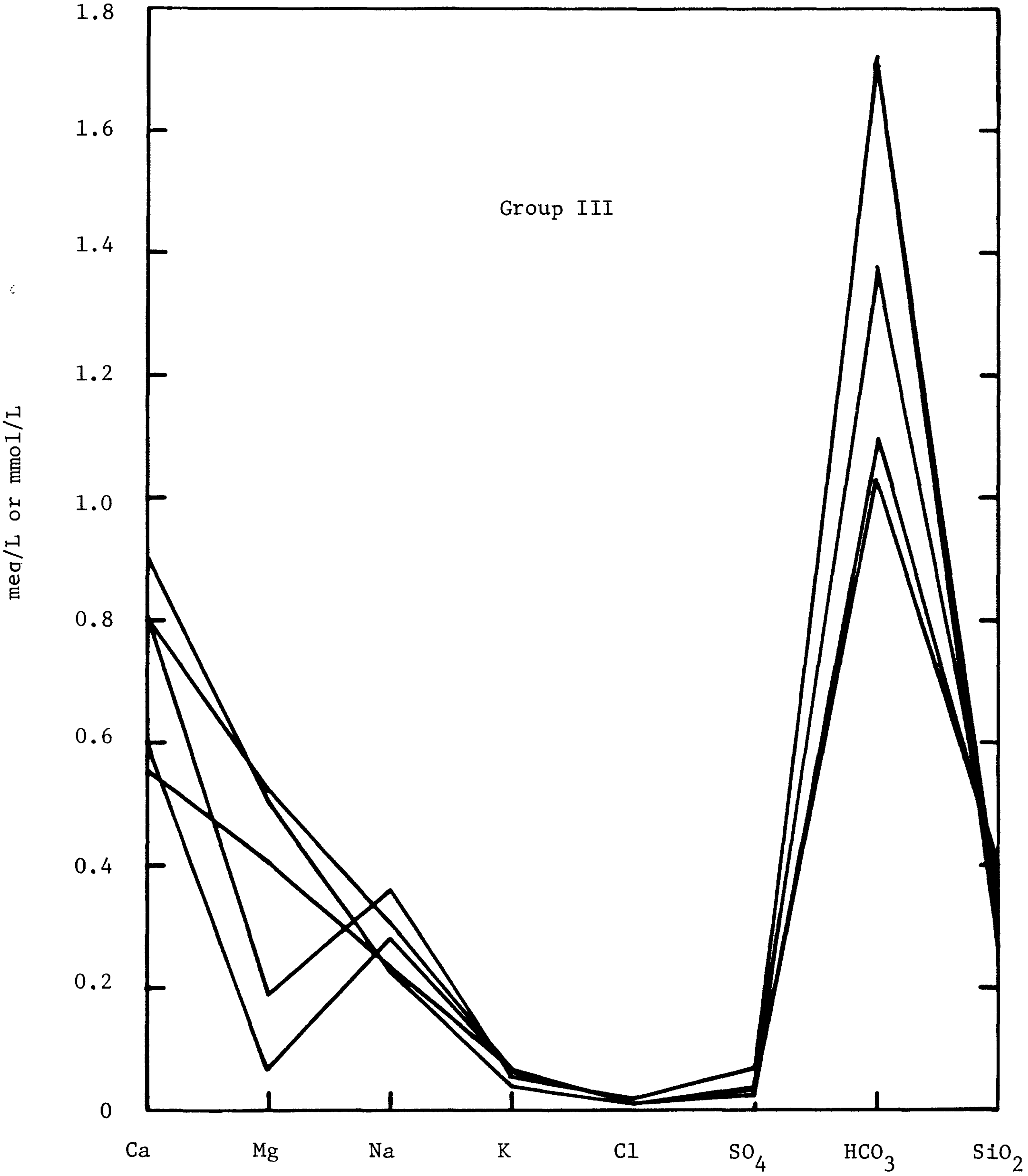

Figure 5. Modified Schoeller plot for water samples in Group III.

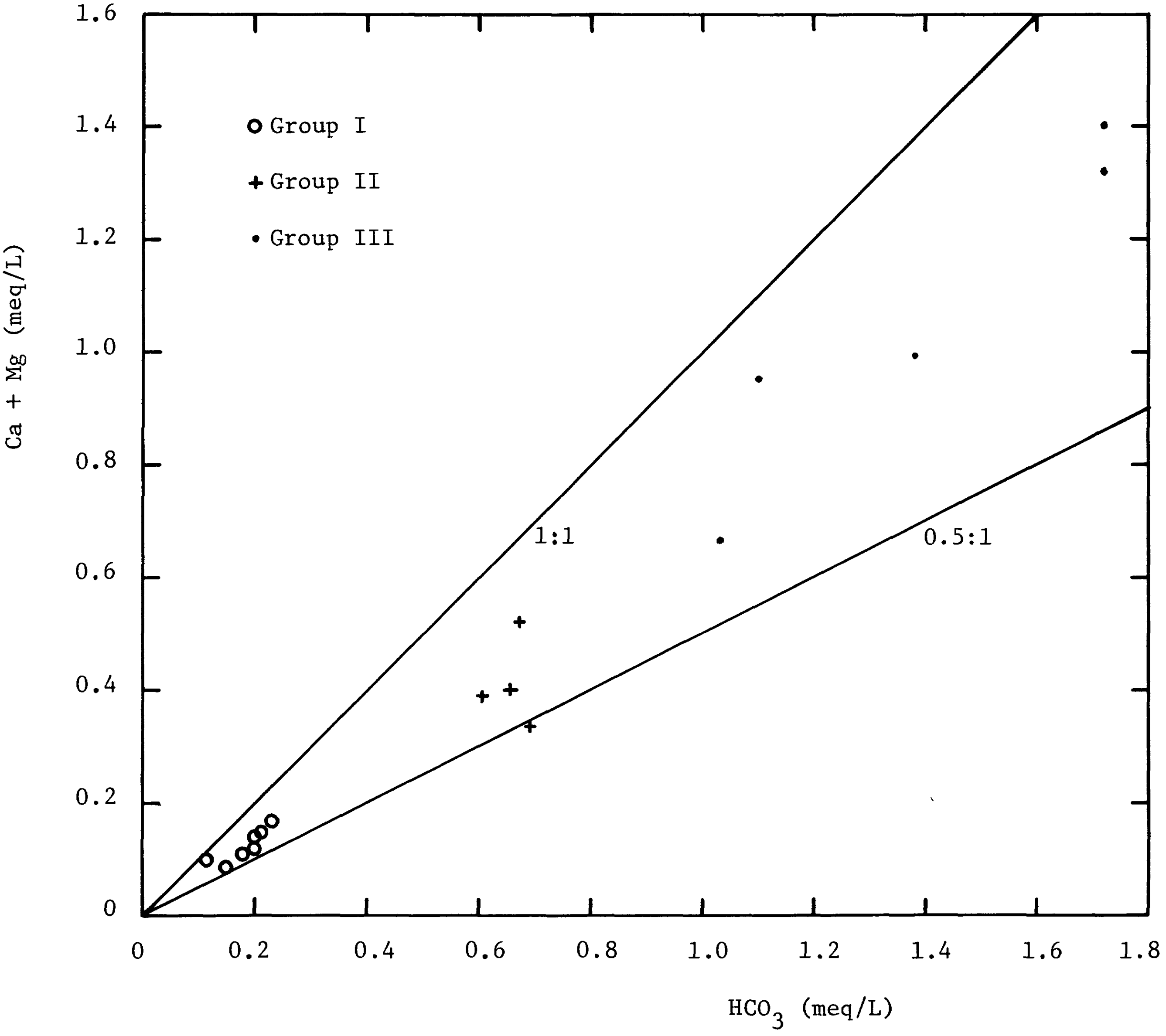

Figure 6. Calcium plus magnesium versus bicarbonate for waters of Groups I, II, and III. Lines are drawn at the slope noted.

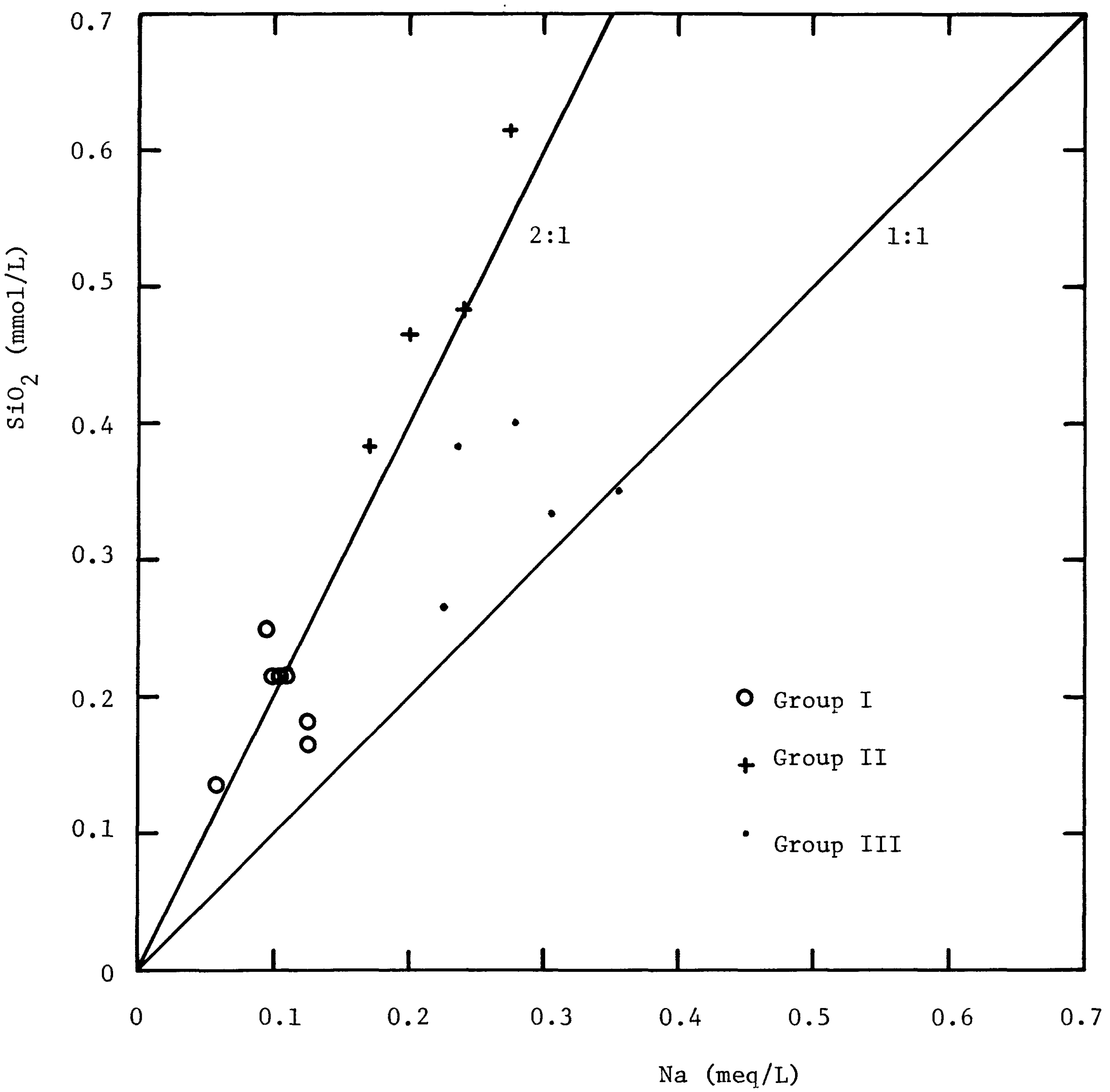

Figure 7. Silica versus sodium for waters of Groups I, II, and III. Lines are drawn at the slope noted.

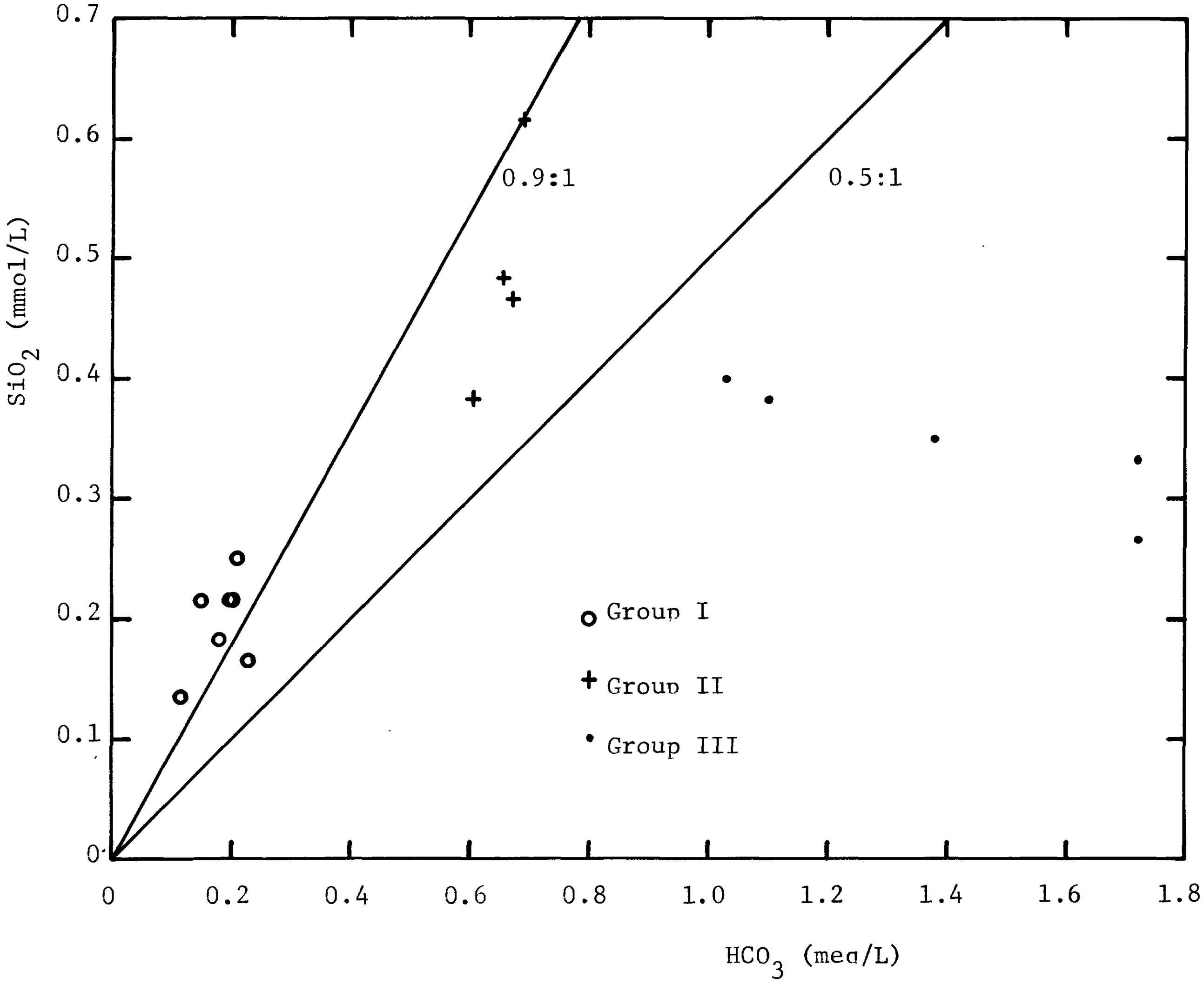

Figure 8. Silica versus bicarbonate for waters of Groups I, II, and III. Lines are drawn at the slope noted.

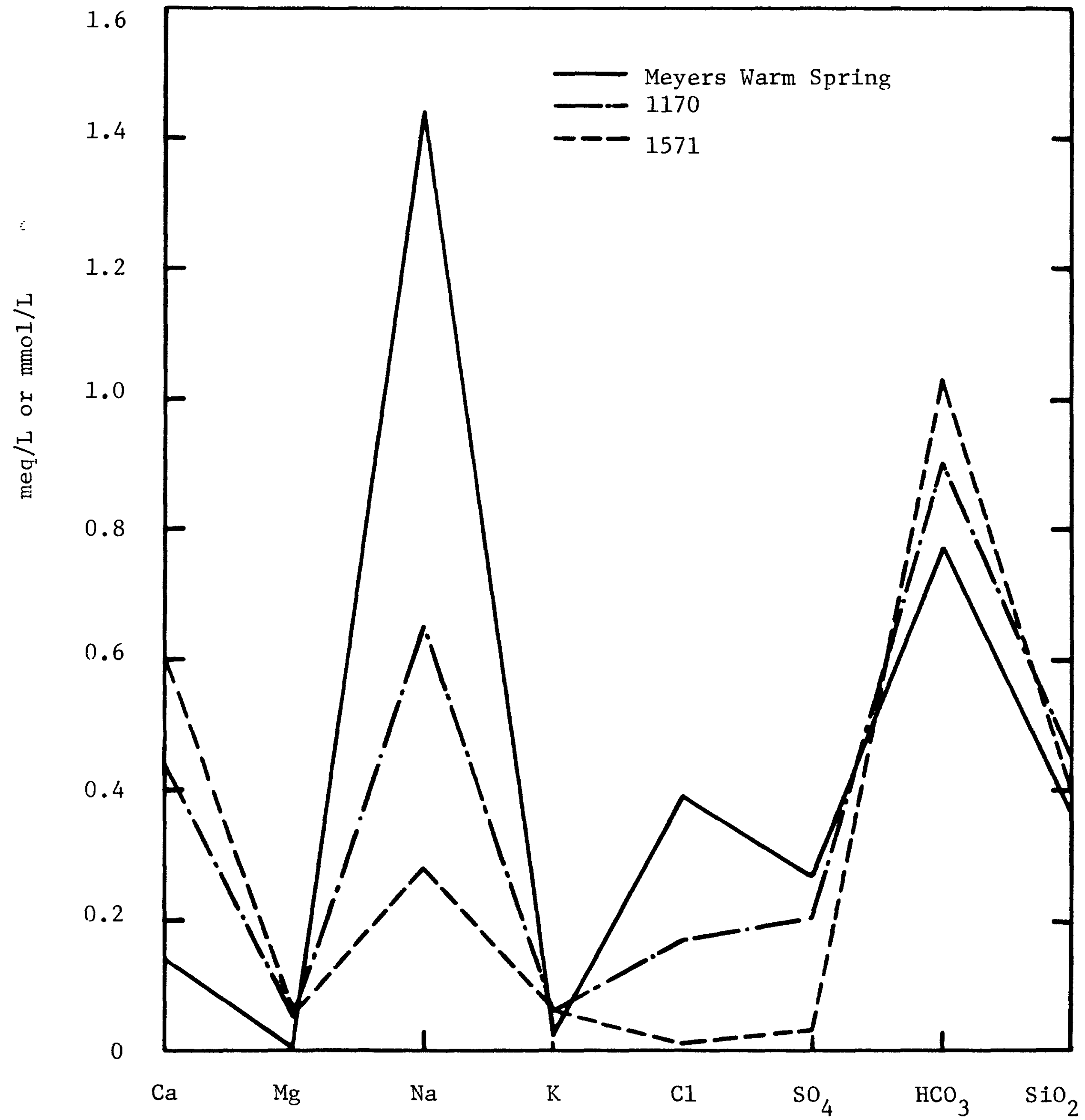

Figure 9. Modified Schoeller plot for water samples from Meyers Warm Spring, cold water sample 1571, and mixed water 1170. Ionic species are in meq/L, and silica is in mmol/L.

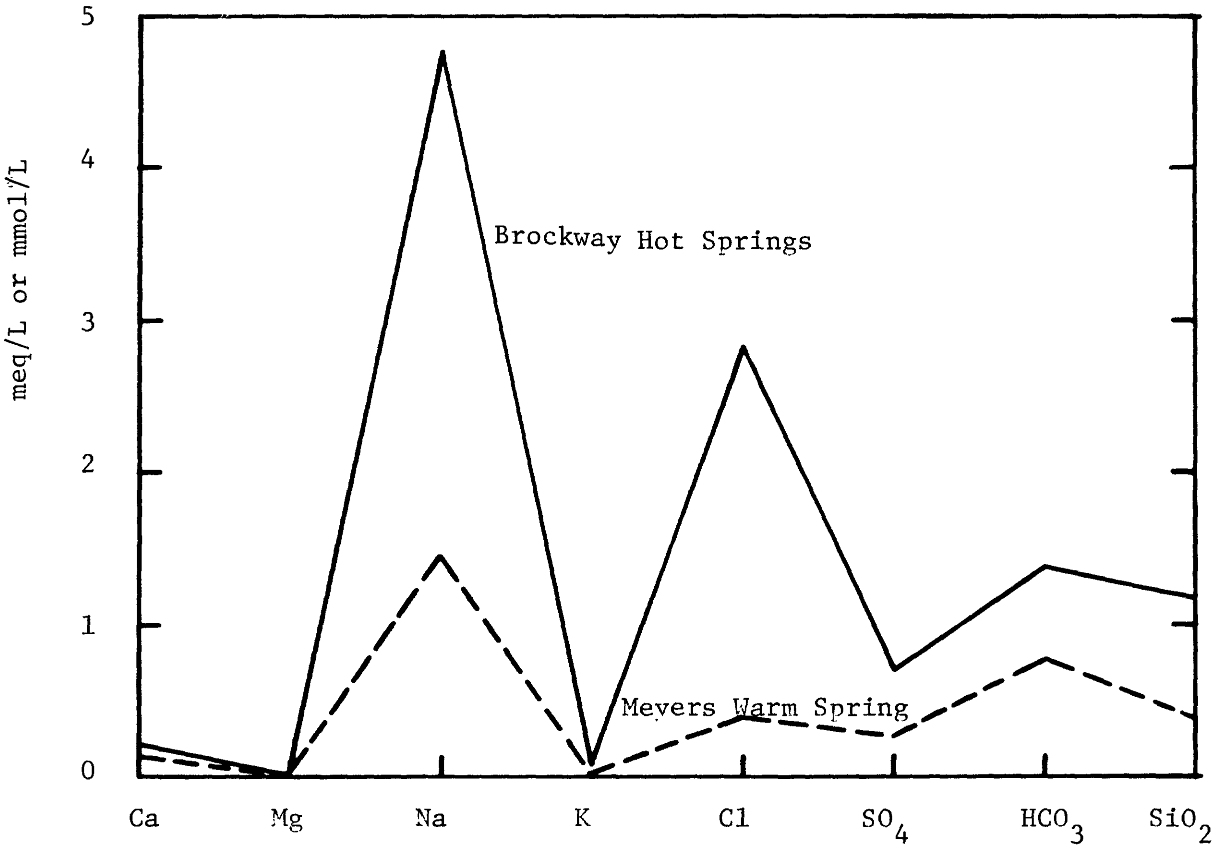

Figure 10. Modified Schoeller plot for water samples from Brockway Hot Springs and Meyers Warm Spring. Note change of scale from previous plots. Ionic species are in meq/L, and silica is in mmol/L.

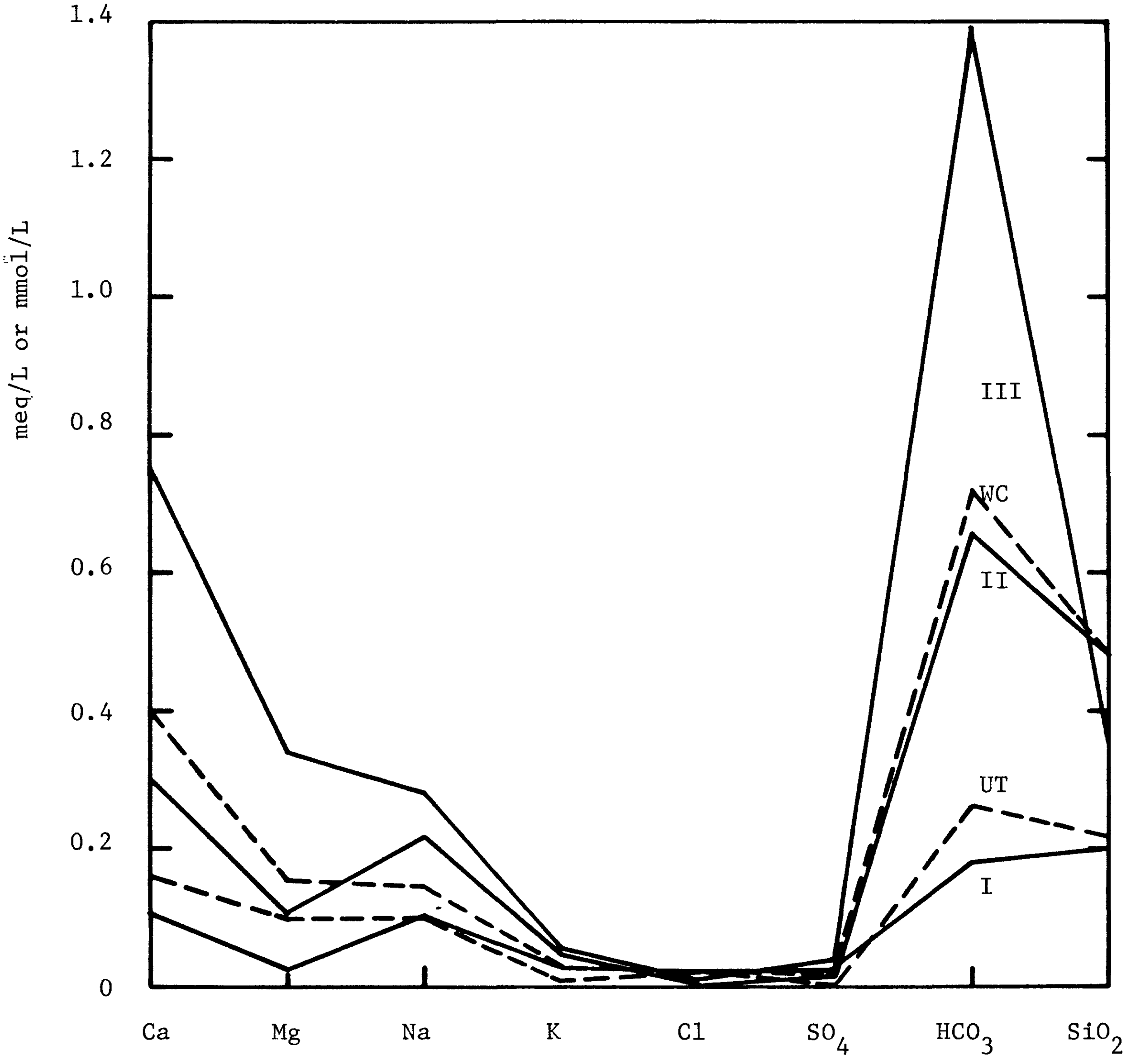

Figure 11. Modified Schoeller plot for samples from the Upper Truckee River (UT), Watson Creek (WC), and averages of Groups I, II, and III. Ionic species are in meq/L, and silica is in mmol/L.

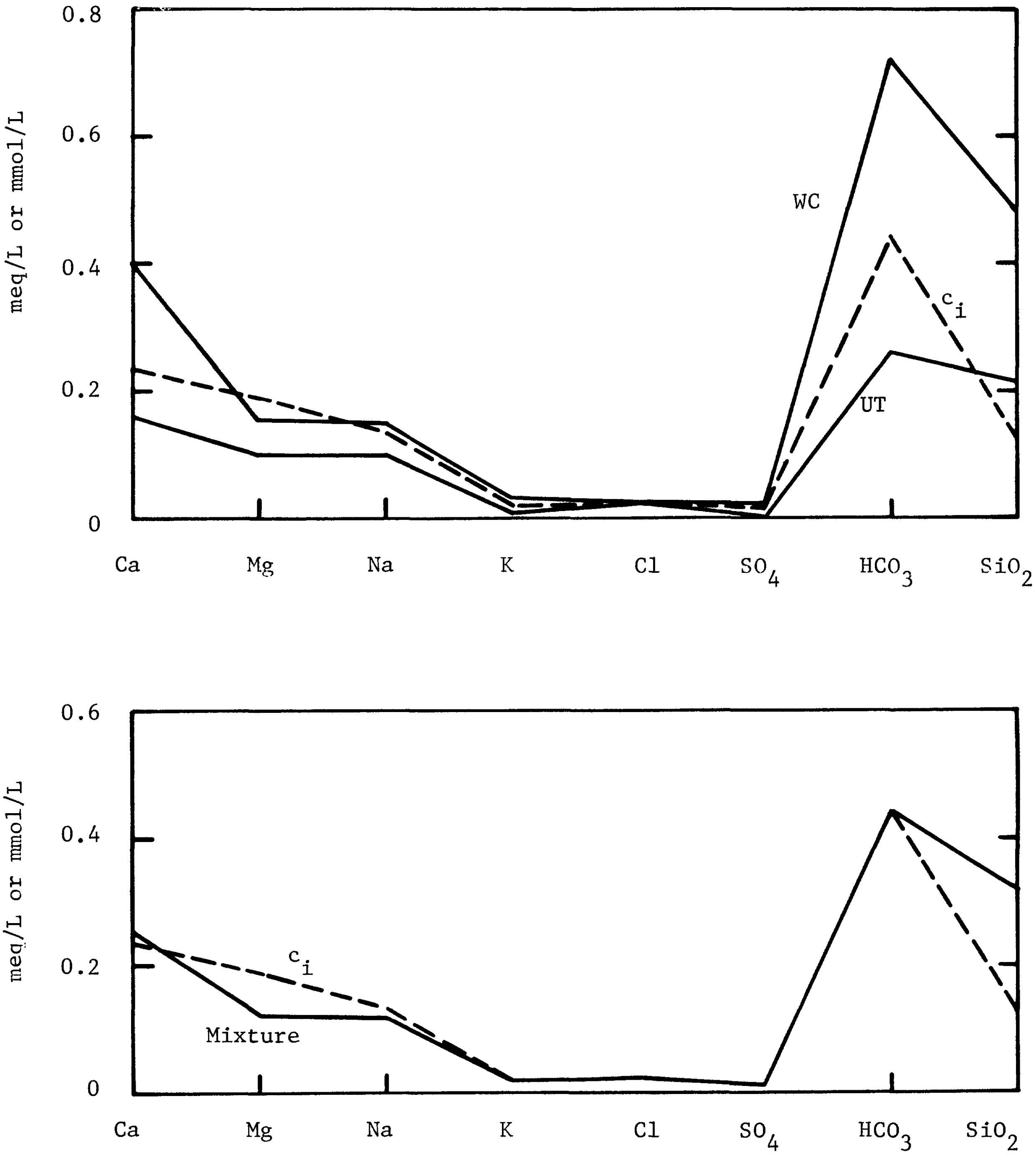

Figure 12. Modified Schoeller plots for samples from the Upper Truckee River (UT), Watson Creek (WC), calculated inflow to Lake Tahoe (c_i), and mixture of 60 % Upper Truckee River water and 40 % Watson Creek water. Ionic species are in meq/L, and silica is in mmol/L.