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ATMOSPHERIC, GEOLOGICAL AND GEOCHEMICAL INFLUENCES ON HIGH MOUNTAIN NORTHERN NEW MEXICO LAKES SUBJECTED TO ACIDIC DEPOSITION

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Abstract—Acidic precipitation has been reported from many parts of the West, including New Mexico. High mountain watersheds may be especially vulnerable because their surficial rocks and soils often have low buffering capacity. A limnological and geological survey of 17 high elevation lakes was conducted in northern New Mexico. Data from five representative lake basins are reported herein. The relative contributions of precipitation and weathering to aqueous chemistry were also examined in one lake. Sedimentation ratios were determined using Cs-137 and Pb-210 geochronology. Lakes were typically small, shallow and colorless. Buffering capacity varied from 8 to 820 μeq/L and was directly related to the surficial geology. Atmospheric contributions to the chemistry of Santa Fe Lake are large in comparison to weathering inputs for all species except HCO_3^- and SiO_2. Half of the sulfate found in lake water originates from the atmosphere. Back-reacting the lake-water chemical constituents attributable to geochemical weathering produced reasonable agreement with minerals present in the basin. Sedimentation rates in three of the five lakes varied from 7 to 13 mm/y. Profiles of Pb-210 in two lakes were anomalous. Sediment profiles of Cs-137 were not representative of the fallout history and were therefore useless for age-dating purposes.

INTRODUCTION

Although acidic precipitation has not been considered a problem in the western U.S., acidic precipitation events have been reported recently in the Sierra Nevada (Melack et al., 1983), the Cascades (Logan et al., 1982), central Colorado (Lewis and Grant, 1980; Huebert et al., 1982; Turk and Adams, 1983; Harte et al., 1985) and in northern and central New Mexico (Popp et al., 1986). The distribution of lakes in the intermountain western U.S. vulnerable to ongoing inputs of acid precipitation is not well known. The U.S. Environmental Protection Agency's (USEPA) Western Lakes Survey (Landers et al., 1987) estimated that 67% of the target lake populations had an acid neutralization capacity (ANC) less than 200 μeq/L. However, only one lake in New Mexico was sampled in the USEPA study. The criterion of 200 μeq/L is used to separate lakes sensitive to acidic deposition from those that are not. Remote lakes at high altitude with low buffering capacities have been reported throughout the West (Eilers et al., 1987), including Rocky Mountain National Park (Baron, 1983), the Flat Tops and Mount Zirkel Wilderness Area of northwestern Colorado (Turk and Adams, 1983; Turk and Campbell, 1987), the Elk Mountains of west-central Colorado (Harte et al., 1985) and the California Sierras (Nodvin, 1988).

High mountain watersheds of northern New Mexico and southern Colorado may also be vulnerable to acidic precipitation. These watersheds receive large quantities of precipitation relative to other locations within the arid Southwest (76–89 cm/y versus 20–30 cm/y), primarily as snow during the winter months and as rain during summer thunderstorms. The soils of these watersheds are derived mainly from Tertiary volcanic and Precambrian crystalline rocks (New Mexico Geological Society, 1982) which characteristically have low neutralization capabilities. Carbonate-rich detritus from Paleozoic sedimentary rocks is abundant in a few places. The soils are typically thin, poorly developed, and are located on steep gradients. Contact time between percolating water and the scarce or absent acid-neutralizing components of the soils is therefore minimal.

The specific objectives of the research reported here were to: (1) document the present pH and buffering capacity of a series of high mountain lakes in northern New Mexico; (2) determine the relative contributions of precipitation and weathering to the aqueous chemistry of one representative lake; and (3) age date the lake sediments to determine sedimentation rates using Cs-137 and Pb-210 geochronology. In this paper, we report results on five lakes which are representative of the three different study areas.

MATERIALS AND METHODS

Sampling: scope of activities

The five lakes in this report were part of a sampling of 17 lakes located in the Pecos Wilderness, Wheeler Peak Wilderness and Brazos uplift areas of north-central New Mexico during the summers of 1986 to 1988 (Figs. 1–4). Data for all the lakes are summarized in Lynch et al. (1988). These lakes are located at elevations exceeding 3000 m and, with the exception of those on the Brazos uplift, were accessible only by foot. Most of the lakes were sampled twice during two different

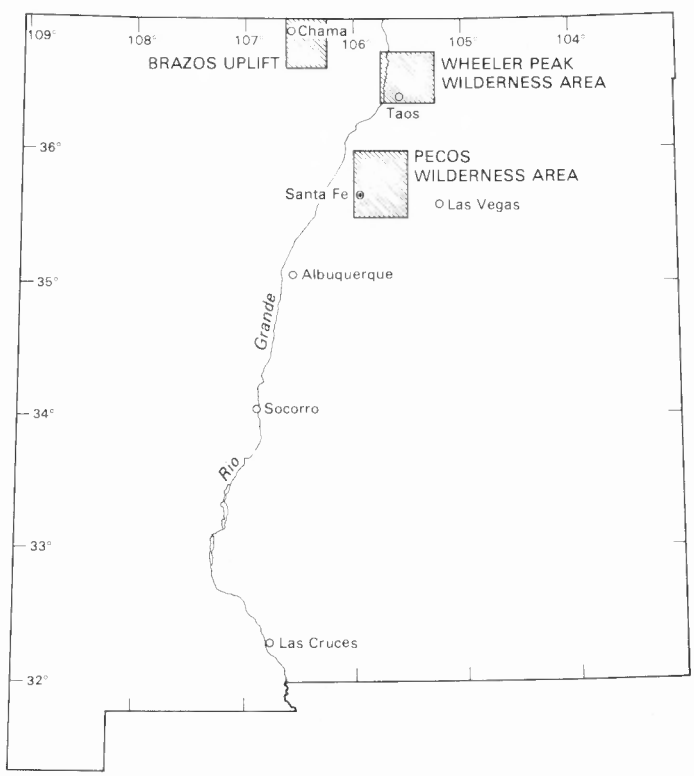


FIGURE 1. Location of study areas.

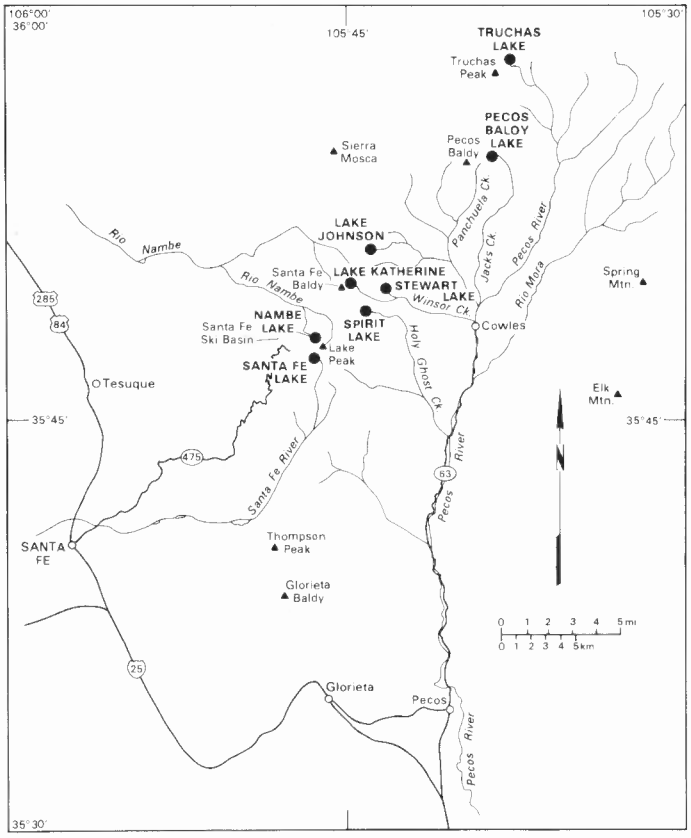


FIGURE 2. Pecos Wilderness study area.

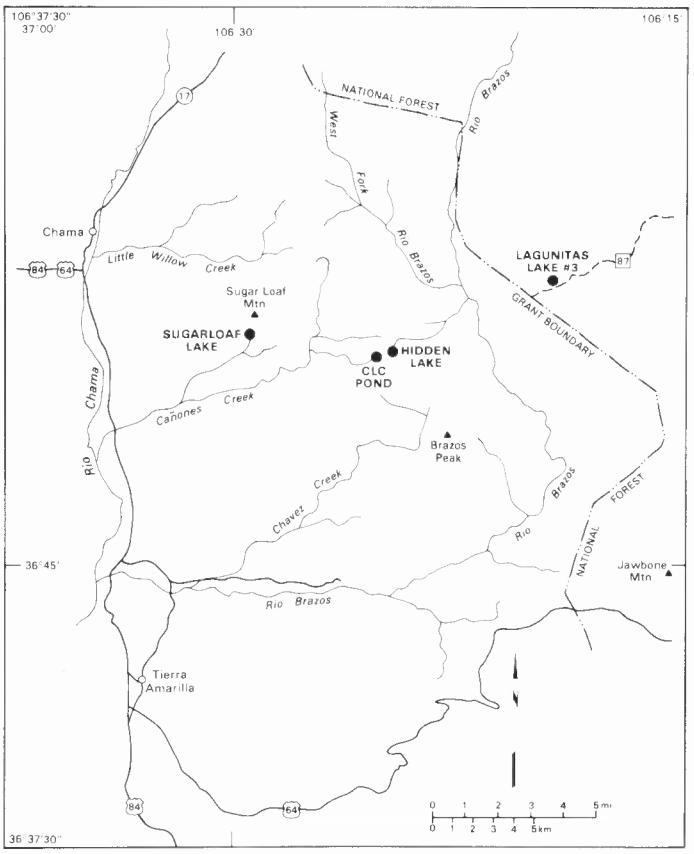


FIGURE 4. Brazos uplift study area.

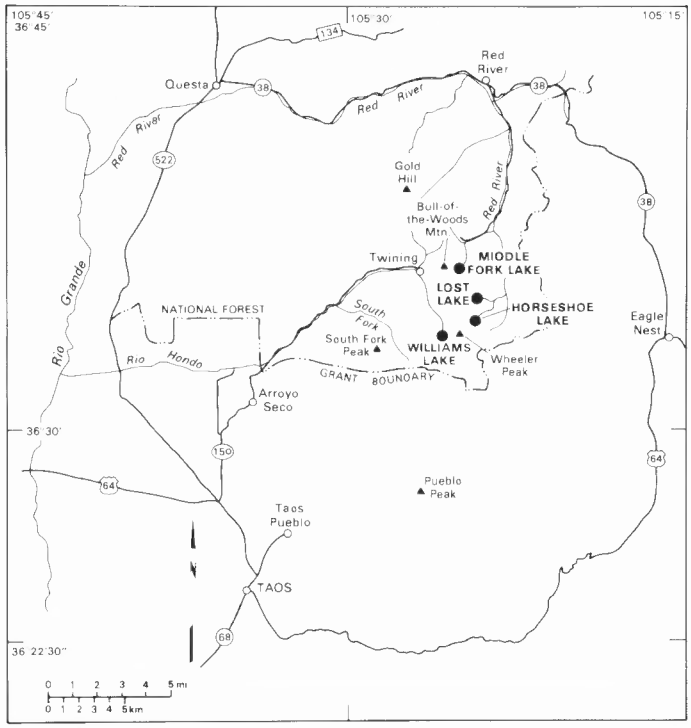


FIGURE 3. Wheeler Peak study area.

summers, whereas Santa Fe Lake in the Pecos Wilderness was sampled in spring, 1986, monthly during 1987–1988, and monthly during the winter of 1988–1989 a total of 21 times. In addition to lake-water samples, snow was collected at several of the lakes. The snowpack at Santa Fe Lake was sampled monthly throughout two winters.

All lakes were sampled extensively on the first visit for a variety of chemical and biological characteristics. The surficial geology of each lake basin was also examined. Lake sampling utilized an inflatable raft as a sampling platform. Surface areas of the lakes and watersheds were calculated using planimetric techniques (Lind, 1979) on enlargements of USGS 7.5′ topographic maps. Lake volumes were calculated from surface areas of the depth contours (plotted from depth soundings) multiplied by the depth interval between contours and then summed.

Water sampling and analysis

Grab samples of midlake surface water were collected for analysis of pH, alkalinity, major cations and anions, aluminum, silica, total and calcium hardness, chlorophyll *a*, dissolved organic carbon (DOC) and total organic carbon (TOC) and total dissolved solids (TDS). Alkalinity and pH were determined in the field. Water samples were filtered through 0.45-μ membrane filters in the field using an Antlia filter pump. Preservation, storage and analytical procedures are described in detail by Lynch et al. (1988) and Peter (1989).

Precipitation sampling and analysis

Where possible, snow was obtained in the summer from remnant drifts along lakeshores and analyzed for pH and ions. More intensive precipitation sampling was conducted at Santa Fe Lake. During the warmer months at Santa Fe Lake, a polyethylene funnel and collection bottle were set out near the lake to collect bulk precipitation. During the colder months, surface snow and the snowpack were sampled. Surface snow samples were collected for chemical analysis by scraping the top 5 cm into polyethylene bottles or plastic Whirl-Pak bags. Once

the snowpack had accumulated, snow pits were dug, and samples were obtained at 30 cm depth intervals for pH and ion analysis for the purpose of monitoring changes throughout the winter and during spring snowmelt (Michaels et al., 1987). Snow samples were melted and brought to room temperature before analysis.

Sediment core sampling and analysis—radioisotope geochronology

Sediment cores were obtained using a modified Brinkhurst core sampler (Brinkhurst et al., 1969). The modification is described in Lynch et al. (1988). After retrieving the core sampler, the tube containing the sediment was removed from the sampler and capped. The core extrusion procedure and sample treatment are described in detail by Lynch et al. (1988).

The activities of Pb-210, Pb-214 and Cs-137 were determined by gamma x-ray analysis using an Ortec high purity N-type germanium detector. All of the samples were counted for approximately 24 hours. Counting procedures and sample preparations are described in Lynch et al. (1988) and Peter (1989).

X-ray diffraction analysis of the less than 2 μ fraction of the lake sediments was also performed using a Rigaku Dmax IIA x-ray diffractometer. A semi-quantitative procedure for the determination of clay was developed by G. S. Austin (oral commun., 1987) and used, and the procedure is described in detail by Peter (1989).

RESULTS AND DISCUSSION

Geologic setting

The Sangre de Cristo Mountains of north-central New Mexico consist of Precambrian igneous and metamorphic (predominantly metavolcanic and metasedimentary clastic) rocks overlain by as much as 600 m of upper Paleozoic clastic and carbonate rocks. In the Wheeler Peak Wilderness area and north to the Colorado border, variable thicknesses of Tertiary volcanic and volcaniclastic rocks commonly lie directly on a Precambrian basement that is intruded by numerous, mainly silicic, Tertiary plutons. A limited number of small, faulted remnants of upper Paleozoic clastic and carbonate rocks sit on the Precambrian basement in the southeastern corner of the Wheeler Peak study area. The Brazos uplift study area also consists of Precambrian igneous and metamorphic rocks directly overlain by a variety of Tertiary volcanic and volcaniclastic rocks. Assorted Pleistocene glacial deposits are developed in the higher elevations of all three study areas. Quaternary landslides are abundant in the two study areas with significant Tertiary rocks.

Lake-water chemistry

The lakes and lake basins described herein were selected to represent the three major regions in the study. The physical characteristics of the lakes are summarized in Table 1. The lakes are small and shallow with low ratios of basin area/surface area (8–100). Ratios with low values increase the possibility that precipitation can have a significant direct effect on lake-water chemistry. Chemical characteristics of the lakes are given in Table 2. Lake water was colorless, and total organic carbon values were low, indicating small contributions from organic acids. Chlorophyll *a* values were also low indicating small algal cell densities. Two of the lakes (Santa Fe and Truchas) exhibit low ANC values that place the lakes in the "sensitive" (<200 μeq/L) to "very sensitive" (<100 μeq/L) categories according to the USEPA guidelines (Landers et al., 1987). These lakes are situated in Precambrian granites, biotite gneisses, quartz diorite and quartzites which have very low buffering capacity. In addition, the pH values of these two lakes occasionally fall below 6.0 (Table 2), which is a borderline pH for many aquatic species to reproduce (Schindler, 1988). The other three lakes included in this report have sufficient buffer capacities and high enough pH values to be insensitive to acidic deposition at this time.

Sugarloaf Lake and Lagunitas Lake #3 are situated in basins containing a variety of Tertiary volcanic and volcaniclastic sandstones and conglomerates and Quaternary landslides containing similar lithologies. Lost Lake is surrounded mainly by Precambrian amphibole gneisses and granite with minor Paleozoic outcrops of sandstones, limestones and shales which provide some neutralization capacity. Of the 17 lakes included in the overall study, eight were in the "sensitive" range for ANC values (Lynch et al., 1988).

TABLE 1. Physical characteristics of lakes.

Region Lake Name	Elevation (m)	Basin Area (ha)	Surface Area (ha)	Basin Area: Surface Area	Maximum Depth (m)	Volume (m^3)
Pecos						
Santa Fe Lake	3,530	15.8	1.9	8.3	7.0	58,000
Truchas Lake	3,618	32.5	1.0	32.5	3.5	16,000
Wheeler Peak						
Lost Lake	3,504	69.9	3.4	20.6	7.5	151,000
Brazos Uplift						
Lagunitas #3 Lake	3,222	24.8	0.4	62.0	3.0	3,700
Sugarloaf Lake	3,005	197.2	2.4	82.2	5.0	42,000

TABLE 2. Chemical limnology of the lakes by study area. Hyphenated values indicate the range of values for samples taken on two or more occasions. TOC = total organic carbon and Chl *a* = chlorophyll *a*. ANC = acid neutralizing capacity. ND = not determined. Zero values for TOC are <0.5 mg/L and Chl *a* <1.9 μg/L.

Study Area and Lake	No. of Samples	pH	ANC (μeg/L)	Hardness (mg/L)	Ca Hardness (mg/L)	TDS (mg/L)	Specific Conductance (25°C μS/cm)	TOC (mg/L)*	Chl a (μg/L)*
Brazos Uplift									
Lagunitas #3	1	8.3	820	45	35	36	94	3.6	6.2
Sugarloaf	2	6.9-8.5	380-480	28-34	17-21	29-48	62	6.6-6.7	3.9-9.7
Pecos Wilderness Area									
Santa Fe	21	5.6-7.1	100-200	9-26	6-27	18-44	16-38	0-4.5	0-137
Truchas	2	5.4-5.5	8-13	3-7	2-3	6-28	4-16	1.9-5.1	0
Wheeler Peak Wilderness Area									
Lost	2	7.7-8.4	580-840	43-45	39	53-70	94-95	0.8-2.1	0-28

Mass-balance approach to origin of chemical composition: Santa Fe Lake

A modified mass-balance approach was used to determine the source of the chemical composition of Santa Fe Lake because the absolute masses of solutes entering and leaving the lake were not measured. This approach has been used by a number of investigators with varying degrees of success (e.g., Garrels and Mackenzie, 1967; Bricker et al., 1968; Cleaves et al., 1970; Reynolds and Johnson, 1972). This method involves subtracting solutes found in precipitation from solutes found in lake water to determine the percentage of the solutes in the lake water that are not atmospherically derived. Solutes not originating from precipitation must come from geochemical weathering reactions within the basin, assuming no other input. Exactly which reactions are occurring may be determined by identifying the weathering products and then back-reacting the products with the solutes to form the minerals present in the basin.

ATMOSPHERIC CONTRIBUTION

Concentrations of solutes in lake water above that found in precipitation were assumed to originate from geochemical weathering as a first approximation. This assumption may underestimate the importance of atmospheric inputs because atmospherically derived solutes can enter the lake basin via dry deposition as well as wet deposition. No studies have been done in this area to determine the importance of dry deposition relative to wet deposition, but studies elsewhere (Barrie et al., 1984; Barrie and Sirois, 1986) determined that dry deposition accounted for 22% of the SO_4^{2-} and 30% of the NO_3^- deposited at six rural sites in eastern Canada.

Dry deposition almost certainly accounts for a significant portion of the atmospheric inputs into Santa Fe Lake. However, the precipitation samples collected at Santa Fe Lake were either collected as snow which

had lain on the ground for long periods of time or as rain collected from an open bucket set out for about 1 month. Because of the time lapse between precipitation events and sample collection, these samples actually represent accumulations of both wet and dry deposition.

Atmospheric contributions to the chemical constituents found in Santa Fe Lake vary considerably depending on the species (Table 3). Nevertheless, atmospheric inputs are quite large in comparison to weathering inputs for all species except HCO_3^- and SiO_2. Approximately one-half of the sulfate found in the lake water originates from the atmosphere. This finding may conflict with the sulfur isotope data of Lynch et al. (1988) which suggested that essentially all of the sulfate in Santa Fe Lake was atmospherically derived. One problem is that there is no readily apparent source of sulfate in the basin. If sulfide minerals (the most likely geologic source of sulfate in the area) are present in the lake basin, they must be microscopic crystals which are not readily visible in surface outcrops. If sulfides do exist in the basin, are oxidized quickly and are isotopically similar to sulfides from which atmospheric sulfate is derived, the sulfur isotope ratios contributed as a consequence of weathering would be similar to those found by Lynch et al. (1988).

Evidence for the reliability of the data in Table 3 is shown by chloride. There are no chloride minerals present in the basin. It is possible that chloride exists as an impurity in non-chloride minerals, but this amount is probably insignificant compared to the amount deposited from the atmosphere. Therefore, the chloride concentrations in both precipitation and lake water should be equal. Table 3 shows that this is very nearly so, the difference between the two being the amount of experimental error. Large contributions of chloride through atmospheric deposition have been observed by Popp et al. (1984) in previous studies in this region.

Atmospheric contributions to the base cations Ca^{2+}, Mg^{2+} and Na^+ in lake water are remarkably similar at about 40% (Table 3). The atmospheric contribution of potassium exceeds 100%. This behavior is probably due to the contribution of precipitation throughfall associated with trees in the basin. Potassium is known to increase in precipitation after falling through canopies of both hardwood (Likens et al., 1977) and spruce forests (Freiesleben et al., 1986), and this effect appears to overwhelm the K^+ available only from atmospheric deposition. Also, it appears from the data that K^+ is held and recycled within the watershed relative to the other base cations.

Nitrate is another species that is not derived from weathering. Table 3 shows that the concentration of NO_3^- is very nearly equal in both precipitation and lake water. However, unlike chloride, NO_3^- can also be derived from the oxidation of NH_4^+, produced by nitrogen-fixing bacteria, and is rapidly cycled by many organisms. The magnitude of biological nitrogen fixation and the effects of nitrogen cycling on the concentration of NO_3^- in Santa Fe Lake is unknown.

MASS-BALANCE DETERMINATION OF WEATHERING REACTIONS FOR SANTA FE LAKE

X-ray diffraction analysis of the Santa Fe Lake sediments showed that the clay-sized fraction was mostly amorphous except for a trace amount of kaolinite (Peter, 1989). Therefore, there are no clearly defined alteration products. On the basis of this, kaolinte was back-reacted with the chemical species in the lake water attributed to geochemical weathering (Table 3) in order to produce minerals present in the basin. Ca^{++} and Na^+ are the two most abundant cations which originate from weathering and are equal in molarity. Because no limestone exists in the basin, the only reasonable source for Ca^{++} and Na^+ is plagioclase feldspar, based on mineralogy. Back-reacting all of the Ca^{++} and Na^+ attributed to weathering with kaolinite gives:

$$5.94\ Al_2Si_2O_5(OH)_4 + 3.95\ Ca^{2+} + 3.96\ Na^+ + 11.80\ HCO_3^- + 7.90\ SiO_2 \longrightarrow 7.91\ Na_{.50}Ca_{.50}Al_{1.50}Si_{2.50}O_8 + 11.80\ CO_2 + 17.78\ H_2O. \quad (1)$$

Thin section examination of quartz diorite and biotite gneiss from the Santa Fe Lake basin showed plagioclase compositions of An_{42} and An_{40}, respectively. Therefore, the plagioclase produced in the above reaction is of a reasonable composition.

Again, based on the surficial geology of the lake basin, biotite is the only reasonable source of Mg^{++}. Assuming an ideal biotite composition, all of the Mg^{++} is back-reacted with kaolinite to make biotite:

$$0.29\ Al_2Si_2O_5(OH)_4 + 1.71\ Mg^{2+} + 0.57\ K^+ + 1.14\ SiO_2 + 3.98\ HCO_3^- \longrightarrow 0.57\ KMg_3AlSi_3O_{10}(OH)_2 + 3.98\ CO_2 + 1.99\ H_2O. \quad (2)$$

The amount of HCO_3^- consumed by the reverse of reactions (1) and (2) (15.78) is about equal to that attributed to weathering (16.0—Table 3). All of the Ca^{2+}, Na^+ and Mg^{2+} are accounted for, while insufficient K^+ and SiO_2 are available. These deficits may be due to incongruent dissolution of mineral grains and contribution of excess K^+ to precipitation and recycling by plants as described earlier, which overemphasized the contribution from precipitation. Experiments by Luce et al. (1972) suggest that weathering of freshly exposed Mg-silicate minerals can result in silica-rich alteration rinds on exposed surfaces. Evidence for similar effects in feldspars has been provided by Paces (1973) and Busenburg and Clemency (1976). If the outer layers of minerals undergoing weathering are silica-enriched then it follows that the solutions participating in the weathering would be silica depleted. In addition, SiO_2 in the lake water is apparently controlled by quartz solubility as described in the next section, which may explain the deficit of soluble SiO_2.

TABLE 3. Chemical species concentrations for Santa Fe Lake water and precipitation collected at Santa Fe Lake averaged from data obtained from monthly sampling. The average concentrations were used to estimate the relative amounts of atmospherically derived and weathering-derived dissolved solids. Standard deviation shown in parentheses and all concentrations are ppm (mg/L).

	Ca^{++}	Mg^{++}	Na^+	K^+	SiO_2	Cl^-	NO_3^-	SO_4^{--}	HCO_3^-
average concentration in lakewater	2.37 (0.41)	0.69 (0.15)	1.70 (0.50)	0.44 (0.14)	1.99 (0.22)	0.40 (0.22)	0.76 (0.55)	2.16 (0.52)	10.22 (1.82)
average concentration in precipitation	0.79 (0.66)	0.28 (0.56)	0.79 (0.73)	0.50 (0.71)	0.18 --	0.55 (0.32)	0.62 (0.54)	1.09 (0.95)	0.41* (0.62)
concentration attributable to weathering (= difference) [molarity x E5 in parentheses]	1.58 (3.95)	0.41 (1.71)	0.91 (3.96)	-0.06	1.81 (3.01)	-0.15	0.12	1.07	9.81 (16.08)
percent of total concentration in lakewater which is atmospherically derived	33%	41%	46%	114%	9%	138%	81%	50%	3%

*Calculated assuming equilibrium with atmospheric CO_2 at 0.0314% corrected to an altitude of 3530 m.

Mineral equilibria and lake-water chemistry

There was some question as to how realistic it is to use kaolinite as the alteration product since only trace amounts showed up in x-ray diffractograms. In order to help answer this question, chemical data from the Santa Fe Lake water samples were evaluated using the chemical equilibria computer program WATEQ (Truesdell and Jones, 1974).

Kaolinite was found to be supersaturated with respect to all 12 of the water samples examined and would be expected to precipitate from solution. Furthermore, all of the primary minerals in the Santa Fe Lake basin that are included in the WATEQ program (albite, anorthite, phlogopite, quartz) were found to be undersaturated, although quartz was only slightly undersaturated. Activities of chemical species calculated by the WATEQ program were plotted on mineral stability diagrams (Riese and Popp, 1980), and all samples were found to plot within the kaolinite stability field.

All of the data examined suggest that kaolinite is the mineral-alteration product being produced in the Santa Fe Lake basin, yet only trace quantities were detected by x-ray diffraction analysis. One explanation is that even if a mineral phase is thermodynamically stable it may not be kinetically favored (Drever, 1982). This explanation is consistent with our results because amorphous phases are always thermodynamically less stable than their corresponding crystalline phases, and amorphous phases also tend to be kinetically favored. In Santa Fe Lake, it appears that a kaolinite amorphous phase is being produced.

Lake sediments: Pb-210 dating and sedimentation rates

Selected radionuclide activities were measured in sediment cores from the five lakes in order to date the sediments with Pb-210, Cs-137 or both. The activity of unsupported Pb-210 was determined by subtracting Pb-214 activity from total Pb-210 activity. Examples of the

data for these isotopes and Cs-137 in Santa Fe Lake are shown in Table 4.

The difference in age between slices in a sediment core was determined from Pb-210 decay using equation 1.

$$t = \frac{-\ln N/N_0}{\lambda}$$

Equation 1. The equation used to determine the difference in age between two successive core slices based on unsupported Pb-210 activity. N_0 = unsupported Pb-210 activity in a core slice, N = unsupported Pb-210 activity in the next slice down in a sediment core, λ is the decay constant which is equal to $3.108 \times 10^{-2} y^{-1}$, and t is the difference in age between the two slices.

Core-slice age was calculated using the distance between the midpoint depths of slices for which unsupported Pb-210 was measured. This distance was divided by the age difference calculated using equation 1. A mean sedimentation rate for the past 100 years for each core was determined based on the age and depth of individual core slices. The data are summarized in Table 5. The sedimentation rates, while similar in the three lakes to which the procedure can be applied, are highest in Truchas Lake which has the highest basin/lake size ratio. Because the half-life of Pb-210 is 22.3 years, this isotopic method can only be used for dating sediments that are less than 5 half-lives old (about 100 years). The Pb-210 in sediments from Santa Fe, Lost and Truchas Lakes exhibited exponential decay profiles, whereas the Pb-210 in sediments from Lagunitas Lake #3 and Sugarloaf Lake did not. Therefore, this method was not applicable to determining sedimentation rates in Sugarloaf Lake or Lagunitas Lake #3.

Sugarloaf Lake is a man-made lake dammed in 1953 (L. Smith, oral commun., 1988) and was subject to mechanical aeration. Sediment redistribution and homogenization probably occurred during aeration operations. The doubt which this problem casts upon the Pb-210 dates combined with the non-exponential Pb-210 profile suggests that Pb-210 cannot be used to date its sediments.

Lagunitas Lake #3 is a natural beaver pond of unknown age. The Pb-210 profile for this lake exhibits the same kinds of problems as the Sugarloaf Lake profile. The profile is non-exponential, and the unsupported Pb-210 activities are very low even in the top core slice. Because of this, the Pb-210 dates for this core are probably not accurate. It is possible that beaver activity and bioturbation has mixed the sediment sufficiently to invalidate the dating procedure.

TABLE 4. Radionuclide activities in pCi/g in the sediment core from Santa Fe Lake. The numbers following the sample I.D. indicate a combination of sediment core slices from top (1) to bottom (12).

Sample	Total Pb-210	Pb-214	Unsupported Pb-210	Cs-137
SF-1,2	27.349	3.145	24.204	5.919
SF-3,5	13.277	3.276	10.001	2.074
SF-6,7	6.650	2.833	3.817	1.204
SF-8,9	4.522	3.188	1.334	1.000
SF-10,11,12	2.746	2.700	0.046	0.771

TABLE 5. Sedimentation rates in mm/y. ND = not determined due to lack of exponential Pb-210 decay.

Lake	Sedimentation Rate	Age of Core Based on Sedimentation Rate-y
Lost	7	207
Sugarloaf	ND	-
Lagunitas	ND	-
Santa Fe	8	219
Truchas	13	158

Cs-137 dating

Cs-137 is an artificial nuclide that did not exist in the environment prior to aboveground nuclear weapons testing in 1945 (Krishnaswami and Lal, 1978). However, Cs-137 was detected at sediment core depths established by Pb-210 dating to be decades older than 1945 (Table 4). Also, maximum Cs-137 activities existed at or near the top of all of the cores. Clearly the Cs-137 activity profiles for the sediment cores are not representative of the fallout history and are therefore useless for dating. Davis et al. (1984) found Cs-137 behaved similarly in soft-water lakes in Scandinavia and New England. They attributed the presence of Cs-137 at pre-fallout depths to molecular diffusion. The surface Cs-137 maxima were attributed to net upward diffusion and adsorption, recycling of sedimentary Cs-137 into the water column and delayed entry into the lake due to absorption in the watershed.

CONCLUSIONS

Of the 17 high altitude lakes in northern New Mexico included in this study, the eight that lie in basins composed entirely of Precambrian rocks are all susceptible to acidic deposition as judged by their alkalinity values. Lakes located in basins containing some calcareous minerals did not exhibit susceptibility to acidic deposition. The most critical time for the aquatic species is at the time of rapid snowmelt when alkalinity and pH values drop suddenly. Additional studies of snowmelt at other low alkalinity lakes should be undertaken to confirm the biological response of some of the zooplankton in Santa Fe Lake to acidic snowmelt.

The approach used for demonstrating the relative contributions of weathering within the watershed and atmospheric deposition to lake-water chemistry using the chemical compositions of wet deposition and lake water, lake-sediment mineralogy and lake-basin geology was successfully demonstrated. Using one of the most potentially sensitive lakes in the region provides a basis for predicting future acidification.

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