

# Ion and Sulfate-Isotope Ratios in Arid Soils Subject to Wind Erosion in the Southwestern USA

WILLIAM H. SCHLESINGER\* AND WILLIAM T. PETERJOHN

## ABSTRACT

Our objective was to evaluate the potential for arid-land soil dusts to contribute significantly to the content of  $\text{SO}_4^{2-}$  and other ions in precipitation. Soil samples collected at 102 locations throughout southwestern USA deserts were extracted with distilled water and analyzed for major ionic constituents and the stable isotope ratios ( $^{34}\text{S}/^{32}\text{S}$ ) in soluble sulfate. Most samples were dominated by  $\text{Ca}^{2+}$  and  $\text{HCO}_3^-$ , and were undersaturated with respect to gypsum. Only a weak correlation was found between  $\text{Ca}^{2+}$  and  $\text{SO}_4^{2-}$  in samples from upland sites. Median  $\delta^{34}\text{S}$  of soil  $\text{SO}_4$  was +6.2‰ compared to +3.9‰ reported for precipitation. However, the median ratios for  $\text{Ca}/\text{SO}_4$  (12.00) and  $\text{Mg}/\text{SO}_4$  (1.84) in soil extracts were much larger than the same ratios in precipitation, suggesting that wind erosion of undisturbed desert soils is not a major source of the  $\text{SO}_4$  in precipitation. Calcite aerosols from desert soils may act to neutralize acid rain in the western USA.

*Additional Index Words:* acid rain, aeolian movements, calcite, deserts, gypsum, stable isotopes, soil chemistry.

WIND EROSION OR DEFLATION WEATHERING is a common feature of arid environments and contributes to the global burden of atmospheric aerosols. In the southwestern USA, major sources of dust include dry lakes (Young and Evans 1986), cultivated land, and unpaved roads (Barnard et al. 1986). Past studies have considered the mass of soil material transported by aeolian processes (Smith et al. 1970, Sinclair 1976, Goudie 1978, Schütz 1980, Hall 1981), but there have been few attempts to examine the contribution of soils to the dissolved ions in precipitation. Many arid soils are characterized by high concentrations of soluble ions, especially those derived from evaporite minerals such as  $\text{NaCl}$ ,  $\text{CaCO}_3$ , and  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  (Schlesinger 1982, Watson 1979). A recent report concluded that the  $\text{Ca}/\text{SO}_4$  ratio of soils in Arizona and Utah was similar to the ratio in rainfall collected at five western stations of the National Atmospheric Deposition Program (NADP) (Creager 1985). Further such studies are needed in light of recent reports of acid rain in the western USA (Lewis and Grant 1980) and the linkage of atmospheric  $\text{SO}_4^{2-}$  concentrations in rainfall to smelter emissions (Oppenheimer et al. 1985, Epstein and Oppenheimer 1986). On a worldwide basis, net aeolian transport of soil sulfate may contribute as much as  $8 \times 10^9$  kg/yr of S, or about 7% of the annual fossil fuel emissions to the atmosphere (Ivanov 1983).

We measured the water-soluble constituents of 123 western soils and compared the ratios between major soil ions to similar ratios reported for precipitation. In addition, we measured the ratio of stable sulfur

isotopes ( $^{34}\text{S}/^{32}\text{S}$ ) in extractable soil  $\text{SO}_4^{2-}$ , and compared these values to the isotopic ratios that are reported for S in coal, oil, and sulfide metal ores and for  $\text{SO}_4^{2-}$  in seawater and rainfall. Our objective was to evaluate the potential for arid-land soil to contribute significantly to the content of  $\text{SO}_4^{2-}$  and other ions in precipitation.

## METHODS

Soils were collected from 102 locations in arid regions of the southwestern USA (Fig. 1). The majority of samples were obtained from alluvial soils forming the piedmont or *bajada* of desert mountain ranges. These areas are typically covered with desert scrub or grassland. Samples were obtained from 13 dry lakes and four cultivated fields to represent habitats that are particularly prone to wind erosion. Field samples of ca. 1 kg were obtained from the upper 5 cm of the soil profile. Samples were also analyzed from the A and B horizons of two Calciorthid soil profiles described by Schlesinger (1985) from the Mojave Desert.

All samples were dried for 24 h at 105 °C and sieved to pass a 2-mm mesh. A 1:5 soil/water extract was prepared using 0.19 kg of soil and 950 mL of distilled water in a 1-L polypropylene bottle. These were shaken for 24 h, and then centrifuged at 838 rad/s for 15 min. Aliquots of the supernatant were filtered through 0.45- $\mu\text{m}$  Millipore HA filters. This filtrate was used for all chemical analyses. A Ross Combination Electrode (Orion 81-02-00) was used to measure pH with an Orion pH meter (Model 701). Alkalinity, expressed as  $\text{mmol L}^{-1}$  of  $\text{HCO}_3^-$ , was determined by titration with 0.01 M  $\text{H}_2\text{SO}_4$  to pH 4.5. Chloride ( $\text{Cl}^-$ ),  $\text{NO}_3^-$ , and  $\text{SO}_4^{2-}$  were determined on a Dionex 2010i ion chromatograph, and  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ , and  $\text{K}^+$  were determined on a Perkin Elmer 370 atomic absorption spectrophotometer.

Ion activities were determined after correcting for ion pairs among all measured constituents using the computer program of Marion and Babcock (1977). The presence of gypsum in the soils was assumed when the pIAP (ion activity product) for  $\text{CaSO}_4$  in the extract was equal to 4.64 (Lindsay 1979). The presence of  $\text{CaSO}_4$  minerals (gypsum, hemihydrate and anhydrite) was also examined by x-ray diffraction using a Phillips x-ray diffraction unit with  $\text{Cu-K}\alpha$  radiation.

Sulfate was precipitated from the remaining supernatant by the addition of  $\text{Ba}^{2+}$ , which was added as 1M  $\text{BaCl}_2$ , in excess of  $\text{SO}_4^{2-}$  concentrations as determined by ion chromatography. The  $\text{BaSO}_4$  precipitate was allowed to settle, the supernatant decanted, and the precipitate dried at 105 °C. When the yield was >10 mg, this crude precipitate was purified using a sodium carbonate fusion, followed by a reprecipitation with  $\text{BaCO}_3$ . The ratio of sulfur isotopes ( $^{34}\text{S}/^{32}\text{S}$ ) was determined in the purified  $\text{BaSO}_4$  and expressed vs. the troilite standard as  $\delta^{34}\text{S}\text{‰}$ . The purification and mass spectrometer analyses were performed by the Global Geochemistry Corp. (Canoga Park, CA).

Statistical analyses were performed using the standard procedures available through the Statistical Analysis System of Cary, NC (Helwig and Council, 1982).

## RESULTS

### Soluble Ions

Calcium dominated the positive charge in most soil samples, accounting for more than half the soluble

Department of Botany, Duke Univ., Durham, NC 27706. This research was supported by WEST Associates under the auspices of the Public Service Company of New Mexico and agreement no. 5027 with Duke Univ. \*For correspondence and reprints. Received 11 May 1987.

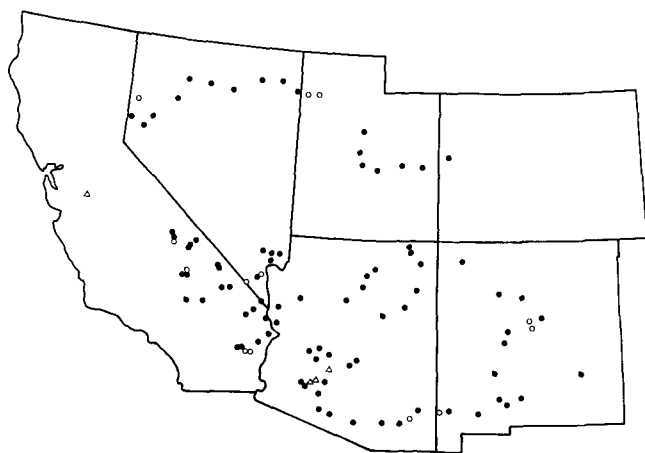


Fig. 1. Field location of 102 sites from which 123 samples of soil were collected in the southwestern U.S. Dry lakes are shown with open circles, and cultivated fields with open triangles; the remaining 106 samples include 96 surface and 10 subsurface soils from undisturbed, upland desert.

cationic charge in 64% of the samples (Fig. 2a). Sodium was the dominant soluble cation in all 13 samples from dry lakes. Among samples from upland sites, soil pH showed a range of 5.47 to 9.46, with a median value of 7.85 (Fig. 3). In dry lakes, pH ranged from 8.22 to 10.91. The total  $H^+$ ,  $Mg^{2+}$  and  $K^+$  was <50% of the soluble cationic charge in nearly all samples.

Among anions,  $HCO_3^-$  accounted for >75% of the soluble negative charge in 71% of the samples,  $SO_4^{2-}$  dominated 11% of the samples, and  $Cl^-$  dominated the remainder (Fig. 2b). Despite high concentrations of soluble  $Ca^{2+}$  and  $HCO_3^-$  in most samples, these constituents were poorly correlated ( $r = -0.05$ ). Instead  $Ca^{2+}$  showed a significant linear correlation with  $SO_4^{2-}$  ( $r = 0.40$ ), but this correlation was largely the result of a few samples with very high soluble concentrations of these ions (Fig. 4). Nitrate was a minor constituent in all samples, averaging <1.0% contribution to the soluble anionic charge. Ion charge balances, calculated for these constituents in the aqueous extracts, showed a mean agreement of +12.1% ( $\pm 2.0\%$  SE). We attribute the excess in positive charge to the presence of anions that were not measured, including organic anions.

The concentrations of soluble ions ( $mmol L^{-1}$ ) were examined using principal components analysis (PCA) to detect major sources of variation among the 113 samples of surface soil. Using a covariance matrix algorithm, the first principal component was highly correlated with Na ( $r = 0.76$ ) and Cl ( $r = 0.58$ ) and explained 94% of the variance among samples (Table 1). The second axis was correlated with Ca ( $r = 0.46$ ) and  $SO_4$  ( $r = 0.74$ ). This analysis was biased by the large effect of samples from saline dry lakes, such as Searles Lake and Owens Lake in California. When all dry lakes were removed from the data set, the first axis explained 96% of the variance and was correlated with Ca ( $r = 0.69$ ) and  $SO_4$  ( $r = 0.73$ ).

Calculated ion activity products for  $CaSO_4 \cdot 2H_2O$  indicated that only 12 soil extracts were in equilibrium with respect to gypsum in the 1:5 soil/water ratio (Fig. 5). As expected, these samples all show Ca/ $SO_4$

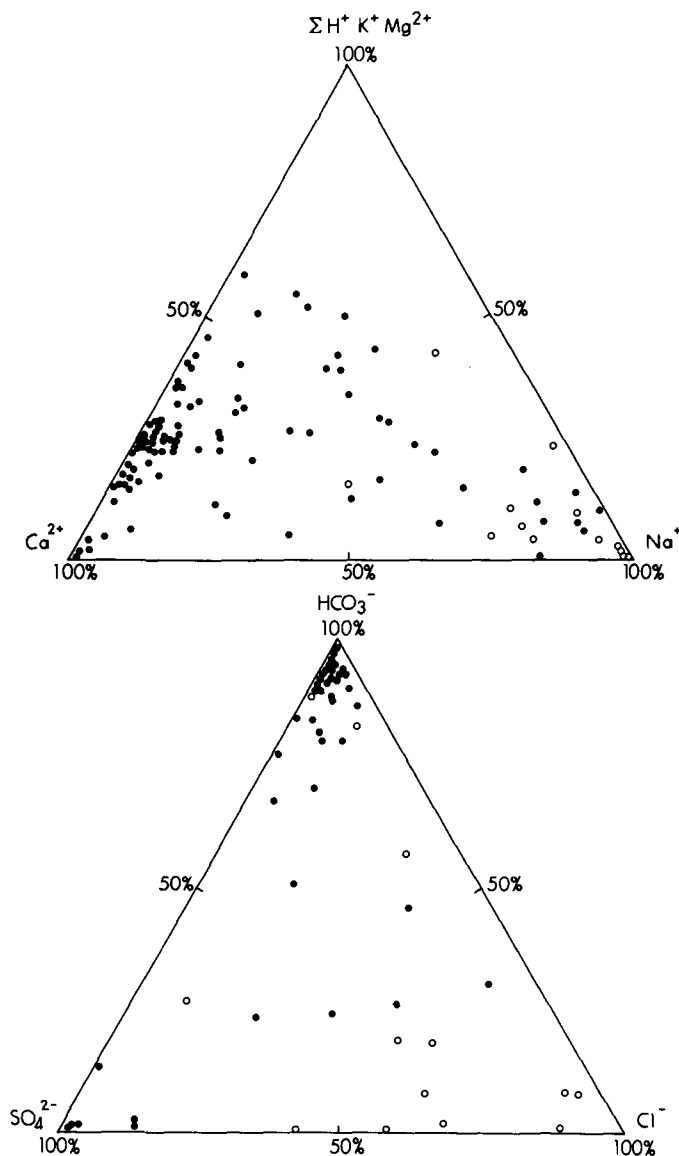


Fig. 2. A. Triangular coordinate plot of the percentage contribution of ions to soluble cationic charge in surface soils. B. Anionic charge. In both cases, the 13 dry lakes are plotted with open circles, and many points are overlapping.

ratios of ca. 1.00, and the presence of one or more  $CaSO_4$  minerals in x-ray diffraction. The Ca/ $SO_4$  ratio varied from 0.001 to 60.0 among the remaining 101 samples, with a median value of 12.0. Samples from upland, alluvial soils of desert scrub or grassland were generally highly undersaturated with respect to gypsum ( $pIAP > 7.00$  in 1:5 extract) and had Ca/ $SO_4$  ratios that were much greater than 1.00 (Fig. 5). However, the x-ray diffraction showed that several of these samples contained small amounts of gypsum, which presumably was completely dissolved yielding undersaturation in the 1:5 extract. Most  $Ca^{2+}$  in these samples is probably derived from contents on the cation exchange sites or from the dissolution of parent or secondary carbonates. The mean Ca/ $SO_4$  ratio for nine samples from calcareous alluvium was 25.0, whereas the mean for 38 samples from igneous and metamorphic parent materials was 18.6.

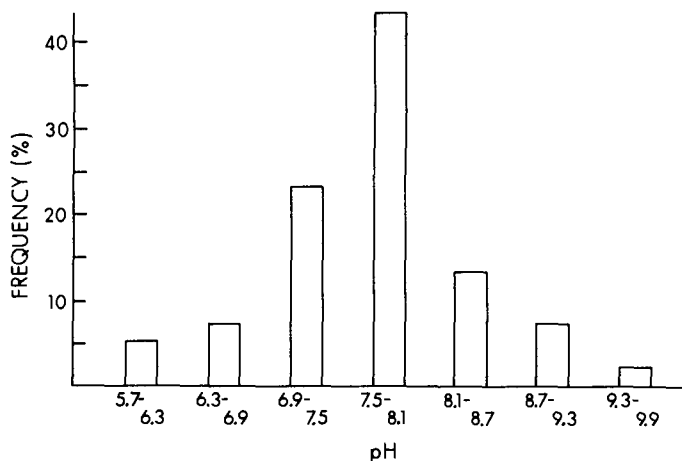


Fig. 3. Frequency of occurrence of pH in soil extracts from upland surface soils.

Among 13 samples from dry lakes, the median Ca/SO<sub>4</sub> ratio was 0.17, indicating the presence of SO<sub>4</sub><sup>2-</sup> in forms other than gypsum. The Ca/SO<sub>4</sub> ratios in Searles and Owens Lakes were <0.01, reflecting the presence of sulfate minerals such as Na<sub>2</sub>SO<sub>4</sub> that are found in these lakes (Holser and Kaplan 1966, Eugster and Hardie 1978). The four cultivated fields had a mean Ca/SO<sub>4</sub> ratio of 0.79 (±0.07 SE). As with Ca/SO<sub>4</sub>, the ratios of Mg/SO<sub>4</sub>, Ca/Na, and Ca/Mg varied over 5 to 6 orders of magnitude among the soil extracts; mean and median values are shown in Table 2.

**Isotope Ratios**

Laboratory replication of mass spectrometer measurements was ±0.35‰ δ<sup>34</sup>S, and analysis of replicate extracts of the same soil samples showed a mean agreement of ±0.81‰. Our value for Searles Lake (+13.4‰) is in reasonable agreement with published values (+14.5‰; Holser and Kaplan 1966). Figure 6

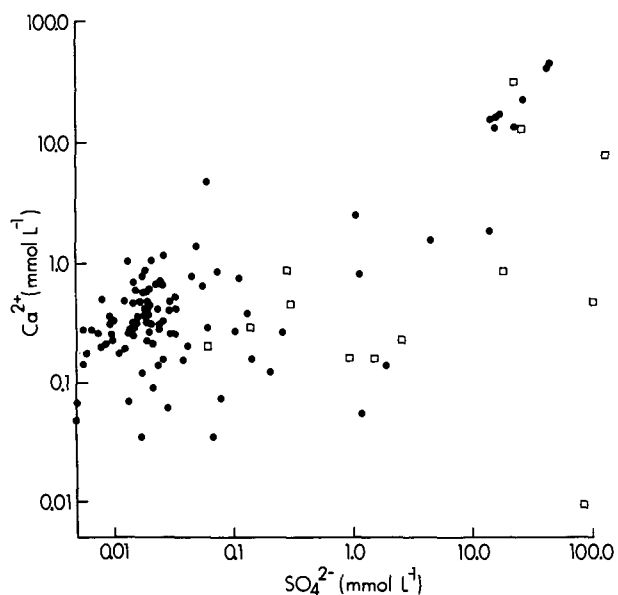


Fig. 4. Ca<sup>2+</sup> and SO<sub>4</sub><sup>2-</sup> concentrations in soil extracts in 113 samples of surface soils; dry lakes are shown with open squares. Logarithmic correlation between these constituents is r = 0.62 (r = 0.78 with dry lakes removed). Linear correlation is r = 0.40; see text.

Table 1. Principal component analysis of extracts of 113 samples of surface soil.†

Correlation	All data		Without dry lakes	
	First axis	Second axis	First axis	Second axis
pH	0.00	0.00	0.00	0.00
HCO <sub>3</sub>	+0.08	-0.17	-0.01	-0.01
Ca <sup>2+</sup>	+0.02	+0.46	+0.69	-0.44
Mg <sup>2+</sup>	+0.07	+0.34	+0.01	+0.03
Na <sup>+</sup>	+0.76	-0.05	+0.03	+0.80
K <sup>+</sup>	+0.02	-0.01	0.00	+0.02
Cl <sup>-</sup>	+0.58	-0.31	+0.01	+0.12
NO <sub>3</sub>	0.00	0.00	0.00	+0.04
SO <sub>4</sub> <sup>2-</sup>	+0.28	+0.74	+0.73	+0.38
Variance explained	0.944	0.029	0.963	0.030

† All data were expressed as mmol L<sup>-1</sup> and the analysis performed in the covariance mode (Helwig and Council 1982).

shows the frequency distribution of δ<sup>34</sup>S in 36 soil samples with sufficient SO<sub>4</sub><sup>2-</sup> for analysis. Most samples cluster around an overall median value of +6.2‰; the median for 13 dry lakes was +7.5‰. Three samples have exceptionally negative values; all of these soils were derived from sedimentary parent materials with high organic content (e.g., Uinta Basin, UT, and Mancos Shale, NM).

Analyses of extractable SO<sub>4</sub><sup>2-</sup> from the upper horizons of alluvial soils derived from the metamorphic parent materials of the Eagle Mountains in eastern California showed no consistent trend in δ<sup>34</sup>S with depth, with values of 4.2, 7.1 and 6.0‰ in the A, B1 and B2 horizons, respectively. Sulfate in these soils is largely derived from the weathering of large concen-

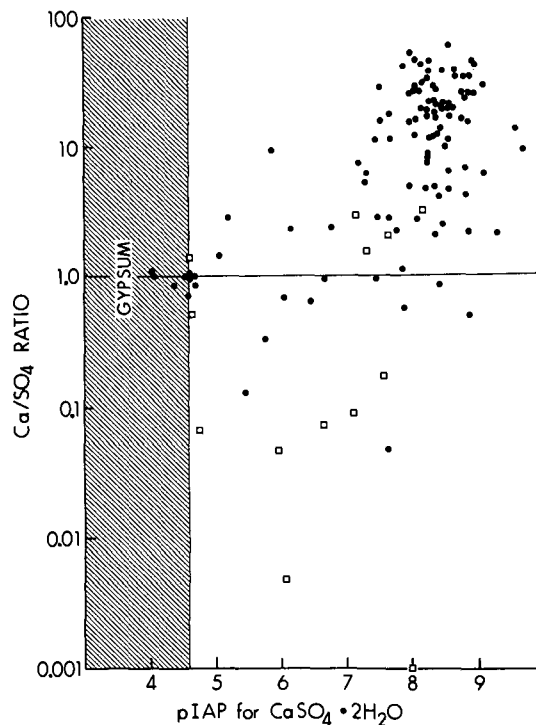


Fig. 5. Ratio of Ca<sup>2+</sup> to SO<sub>4</sub><sup>2-</sup> in extracts of 123 soils as a function of the ion activity product for CaSO<sub>4</sub>·2H<sub>2</sub>O; pIAP < 4.64 indicates equilibrium with respect to gypsum in the solid phase. Samples in which gypsum is the dominant soluble mineral should show Ca/SO<sub>4</sub> = 1.00. Dry lakes are shown with open squares; several points are overlapping in the area of equilibrium with respect to gypsum.

**Table 2. Mean and median values for ionic ratios in extracts of surface soil and reported for aerosols and precipitation in the southwestern USA.**

	Ca/SO <sub>4</sub>		Mg/SO <sub>4</sub>		Ca/Na		Ca/Mg		δ <sup>34</sup> S	
	Mean	Median	Mean	Median	Mean	Median	Mean	Median	Mean	Median
All soils	14.82	12.00	2.62	1.84	65.22	9.64	14.62	6.80	4.0	6.2
Dry lakes	0.93	0.17	0.22	0.09	0.18	0.06	5.44	4.50	8.5	7.5
Agricultural fields	0.79	0.78	0.20	0.17	1.12	0.70	4.97	4.85	2.0	3.4
Aerosols†	0.51		0.19		3.24		2.66			
Precipitation		0.72‡		0.24‡		3.64‡		3.80‡	3.9§	

† Moyers et al. (1977) southeastern Arizona.

‡ Creager (1985), five western NADP stations.

§ Popp et al. (1986), New Mexico.

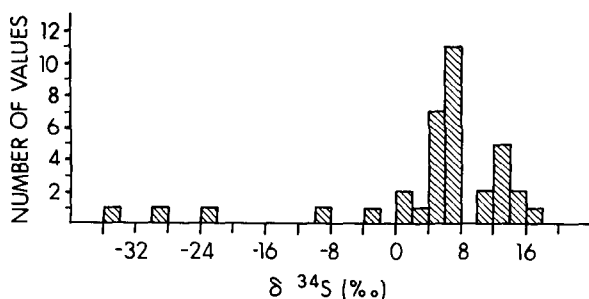
trations of pyrite that was deposited during hydrothermal alteration of the parent rocks (DuBois and Brummett 1968). Alluvium from the Coxcomb Mountains, ca. 10 km NE of these pits, had an average δ<sup>34</sup>S of +6.4‰. This soil is derived from the weathering of granodiorite with much lower pyrite content. A dry lake receiving runoff from both of these areas had δ<sup>34</sup>S of +6.6‰ in extractable SO<sub>4</sub><sup>2-</sup>.

## DISCUSSION

Differences in the chemical composition of the soil extracts reflect well-known differences in the geochemical distribution of soluble ions among landscape positions in arid environments (Drever and Smith 1978). In upland soils, inhabited by desert scrub and grassland, Ca<sup>2+</sup> dominates the cationic charge. This Ca<sup>2+</sup> is derived from weathering of parent materials or from aeolian inputs of carbonate dust. In most cases, the Ca<sup>2+</sup> is balanced by HCO<sub>3</sub><sup>-</sup> derived from carbonation weathering. These ions are relatively abundant in surface horizons despite their continual eluviation to the lower soil profile, a process that eventually results in the formation of calcic horizons or caliche (Gile et al. 1966, Schlesinger 1985). There is relatively little movement of Ca<sup>2+</sup> to downslope positions or net loss from the ecosystem (Lajtha and Schlesinger, in press).

In contrast, SO<sub>4</sub><sup>2-</sup>, Na<sup>+</sup> and Cl<sup>-</sup> are more mobile than Ca<sup>2+</sup> and tend to be removed from the ecosystem (Drever and Smith 1978). Thus, in upland soils Ca/SO<sub>4</sub> is typically >> 1.00, and gypsum is absent (Fig. 5). Nevertheless, when parent materials contain exceptionally high concentrations of weatherable SO<sub>4</sub><sup>2-</sup> or pyrite, Ca<sup>2+</sup> and SO<sub>4</sub><sup>2-</sup> may dominate the ionic balance in surface horizons and CaSO<sub>4</sub>·2H<sub>2</sub>O may accumulate in the lower profile. The occurrence of a few such samples results in an overall correlation between the ionic charge of Ca<sup>2+</sup> and SO<sub>4</sub><sup>2-</sup> among soil samples (Fig. 4) and high weightings for these ions in principal components analysis of upland sites (Table 1).

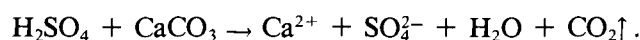
Highly mobile ions, Na<sup>+</sup> and Cl<sup>-</sup>, are leached from

**Fig. 6. Occurrence of δ<sup>34</sup>S among 36 samples with sufficient extractable SO<sub>4</sub><sup>2-</sup> for isotopic analysis.**

upland positions and accumulate in dry lakes and floodplain soils. Many of these areas also show Ca/SO<sub>4</sub> << 1.00, as a result of the accumulation of SO<sub>4</sub><sup>2-</sup>. A useful index of comparative landscape position is the ratio Ca/Na, which tends to be much higher in upland soils than in dry lakes (Table 2).

Ratios of ions have long been used to deduce the sources of constituents in precipitation (Junge 1963). Several recent papers have also compared the elemental ratios in soil and aerosol particles (e.g., Moyers et al. 1977, Flocchini et al. 1981). Most of these comparisons are based on total element analyses. To examine the potential contribution of soils to the dissolved constituents in rainfall, the ratios among ions that can be dissolved from soils during a relatively short extraction with water may provide more realistic comparisons. Our data suggest that the vast majority of desert soils are an unlikely source for much of the SO<sub>4</sub><sup>2-</sup> in precipitation. The Ca/SO<sub>4</sub>, Mg/SO<sub>4</sub>, and Ca/Na ratios in most soil extracts are all much larger than ratios measured in precipitation at western NADP stations (Table 2). Except for Ca/Na, however, the ratios of these ions in soils from dry lakes and cultivated fields are relatively close to the ratios that are found in precipitation. Large amounts of dust are typically generated in these areas from "dust devils" and cultivation (Hall 1981). We caution against an overinterpretation of the data from cultivated fields, because the sample size is small ( $n = 4$ ) and because most samples are from a relatively small area in the Gila River sediments of Arizona.

Many workers have reported calcite as a dominant constituent of aeolian dust from arid regions (e.g., Goudie 1978, Ganor and Mamane 1982, Pewe et al. 1981, Loÿe-Pilot et al. 1986, Nativ and Mazor 1987, Litaor 1987). Anthropogenic SO<sub>2</sub>, forming H<sub>2</sub>SO<sub>4</sub> in cloud water, may be neutralized by reaction with calcite aerosols in raindrops



This reaction would produce strong correlations between Ca and SO<sub>4</sub> among the dissolved constituents in rainfall, with the excess CaCO<sub>3</sub> remaining as undissolved calcite. Such correlations, and Ca/SO<sub>4</sub> ratios of ca. 1.0 are commonly reported in western rainfall (Creager 1985, Hidy 1986); whereas in the eastern USA, SO<sub>4</sub> is more highly correlated with H<sup>+</sup>.

Sulfur isotopes vary among major geochemical reservoirs of sulfur on the Earth's surface (Holser and Kaplan 1966). Of significance here is δ<sup>34</sup>S in the major potential sources of atmospheric SO<sub>4</sub><sup>2-</sup> (Nielsen 1974). Sulfate in modern seawater has an isotopic ratio of +20‰, and sulfate in marine evaporite deposits has varied from +10 to +30‰ through geologic time. Al-

though sedimentary sulfides average  $-12\%$  (Holser and Kaplan 1966), organic sulfur in coal and oil ranges from  $-10\%$  to  $+20\%$  depending on the source (Nielsen 1974, Krouse and McCready 1979). Average values are  $+5\%$   $\delta^{34}\text{S}$ . Sulfide metal ores show a similar distribution of values (Nielsen 1974).

There are relatively few measurements of  $\delta^{34}\text{S}$  in  $\text{SO}_4^{2-}$  of precipitation. Nriagu and Coker (1978) report higher values ( $+6.4\%$ ) in winter than in summer ( $+2.9\%$ ) for 19 stations in the Great Lakes Region (cf. Nriagu et al. 1987). Recently Popp et al. (1986) measured a mean value of  $3.91 \pm 1.1\%$  for 18 samples taken at three locations in New Mexico. Grey and Jensen (1972) report a mean value of  $9.0 \pm 0.3\%$  for samples in remote areas in northern Utah.

Little is known about the abundance of S isotopes in desert soils that might yield sulfate-rich aerosols to the atmosphere (Ivanov 1983). Our median value of  $+6.2\%$  for  $\delta^{34}\text{S}$  in  $\text{SO}_4^{2-}$  extractable from the surface soils of southwestern deserts is similar to the values measured in rainfall in this region (Table 2); however, a similar range of values from other potential sources makes a direct linkage between soil dust and rainfall equivocal. Previous workers, assuming that the  $\delta^{34}\text{S}$  of soil gypsum is similar to that in marine evaporites ( $+20\%$ ) have dismissed soil dust as a potential source of  $\text{SO}_4$  in rainfall (Popp et al. 1986). Significantly, our values for soil  $\text{SO}_4$  suggest that the  $\delta^{34}\text{S}$  ascribed to marine evaporites cannot be applied to soil  $\text{SO}_4^{2-}$  or soil gypsum that has precipitated in desert ecosystems.

#### ACKNOWLEDGMENT

We thank Dr. Ron Amundson, Evan DeLucia, Paul Fonteyn, Kate Lajtha, Stan Smith and Ralph Williams for help in obtaining soil samples. Dr. Giles Marion made his computer program available for the calculation of ion activities in the soil solutions, and deserves special thanks. Dr. Dan Binkley, Dan Livingstone, Wes Jarrell and William Reiners provided helpful reviews of the manuscript.

#### REFERENCES

- Barnard, W.R., G.J. Strenslund, and D.F. Gatz. 1986. Alkaline materials flux from unpaved roads: Source strength, chemistry and potential for acid neutralization. *Water, Air, Soil Pollut.* 30:285-293.
- Creager, C.S. 1985. Characterization of the influence of soil particulates on precipitation chemistry at five sites in the western United States. Report 0785-224-ID. Kilkelly Environ. Assoc., Raleigh, NC.
- Drever, J.I., and C.L. Smith. 1978. Cyclic wetting and drying of the soil zone as an influence on the chemistry of ground water in arid terrains. *Am. J. of Sci.* 278:1448-1454.
- DuBois, R.L., and R.W. Brummett. 1968. Geology of the Eagle Mountain mine area. p. 1592-1606. *In* J.D. Ridge (ed.) Ore deposits of the United States, 1933-1967. *Am. Inst. Min., Metall. Petr. Eng.*, New York.
- Epstein, C.B., and M. Oppenheimer. 1986. Empirical relation between sulphur dioxide emissions and acid deposition derived from monthly data. *Nature (London)* 323:245-247.
- Eugster, H.P., and L.A. Hardie. 1978. Saline Lakes. p. 237-293. *In* A. Lerman (ed.) Lakes: Chemistry, geology and physics. Springer-Verlag, New York.
- Flocchini, R.G., T.A. Cahill, L.L. Ashbaugh, R.A. Eldred, and M. Pitchford. 1981. Seasonal behavior of particulate matter at three rural Utah sites. *Atmos. Environ.* 15:315-320.
- Ganor, E., and Y. Mamane. 1982. Transport of Saharan dust across the eastern Mediterranean. *Atmos. Environ.* 16:581-587.
- Gile, L.H., F.F. Peterson, and R.B. Grossman. 1966. Morphological and genetic sequences of carbonate accumulation in desert soils. *Soil Science* 101:347-360.
- Goudie, A.S. 1978. Dust storms and their geomorphological implications. *J. Arid Environ.* 1:291-310.
- Grey, D.C., and M.L. Jensen. 1972. Bacteriogenic sulfur in air pollution. Science (Washington, DC) 177:1099-1100.
- Hall, F.F. 1981. Visibility reductions from soil dust in the western U.S. *Atmos. Environ.* 15:1929-1933.
- Helwig, J.T., and K.A. Council. 1982. SAS user's guide. Statistical Analysis System Inst., Raleigh, NC.
- Hidy, G.M. 1986. Acid deposition in the western United States. *Science (Washington, DC)* 233:10.
- Holser, W.T., and I.R. Kaplan. 1966. Isotope geochemistry of sedimentary sulfates. *Chem. Geol.* 1:93-135.
- Ivanov, M.V. 1983. Major fluxes of the global biogeochemical cycle of sulphur. p. 449-463. *In* M.V. Ivanov and J.R. Freney (ed.) The global biogeochemical sulphur cycle. John Wiley & Sons, Inc., New York.
- Junge, C.E. 1963. Air chemistry and radioactivity. Academic Press, New York.
- Krouse, H.R., and R.G.L. McCready. 1979. Reductive reactions in the sulfur cycle. p. 315-368. *In* P.A. Trudinger and D.J. Swaine (ed.) Biogeochemical cycling of mineral-forming elements. Elsevier Scientific Publishing Co., Amsterdam.
- Lajtha, K., and W.H. Schlesinger. The biogeochemistry of phosphorus cycling and phosphorus availability along a desert soil chronosequence. *Ecology* (in press).
- Lindsay, W.L. 1979. Chemical Equilibria in Soils. John Wiley & Sons, Inc., New York.
- Litaor, M.I. 1987. The influence of eolian dust on the genesis of alpine soils in the Front Range, Colorado. *Soil Sci. Soc. Am. J.* 51:142-147.
- Lewis, W.M., and M.C. Grant. 1980. Acid precipitation in the western United States. *Science (Washington, DC)* 207:176-177.
- Loye-Pilot, M.D., J.M. Martin, and J. Jorelli. 1986. Influence of Saharan dust on the rain acidity and atmospheric input to the Mediterranean. *Nature* 321:427-428.
- Marion, G.M., and K.L. Babcock. 1977. The solubilities of carbonates and phosphates in calcareous soil suspensions. *Soil Sci. Soc. Am. J.* 41:724-728.
- Moyers, J.L., L.E. Ranweiler, S.B. Hopf, and N.E. Korte. 1977. Evaluation of particulate trace species in southwest desert atmosphere. *Environ. Sci. Technol.* 11:789-795.
- Nativ, R., and E. Mazor. 1987. Rain events in an arid environment—Their distribution and ionic and isotopic composition patterns: Makhtest Ramon Basin, Israel. *J. Hydrol. (Amsterdam)* 89:205-237.
- Nielsen, H. 1974. Isotopic composition of the major contributors to atmospheric sulfur. *Tellus, Ser. B* 26:213-221.
- Nriagu, J.O., and R.D. Coker. 1978. Isotopic composition of sulfur in precipitation within the Great Lakes Basin. *Tellus, Ser. B* 30:365-375.
- Nriagu, J.O., D.A. Holdway, and R.D. Coker. 1987. Biogenic sulfur and the acidity of rainfall in remote areas of Canada. *Science (Washington, DC)* 237:1189-1192.
- Oppenheimer, M., C.B. Epstein, and R.E. Yuhnke. 1985. Acid deposition, smelter emissions, and the linearity issue in the western United States. *Science (Washington, DC)* 229:859-862.
- Pewe, T.L., E.A. Pewe, R.H. Pewe, A. Journaux, and R.M. Slatt. 1981. Desert dust characteristics and rates of deposition in central Arizona. *U.S. Geol. Surv. Prof. Pap.* 186:169-190.
- Popp, C.J., D.K. Brandvold, A. Long, and L. Warneke. 1986. Acid precipitation in western North America: Trends, sources, and altitude effects in New Mexico 1979-1985. *Water, Air, Soil Pollut.* 30:125-133.
- Schlesinger, W.H. 1982. Carbon storage in the caliche of arid soils: A case study from Arizona. *Soil Science* 133:247-255.
- Schlesinger, W.H. 1985. The formation of caliche in soils of the Mojave Desert, California. *Geochim. Cosmochim. Acta* 49:57-66.
- Schütz, L. 1980. Long range transport of desert dust with special emphasis on the Sahara. *Ann. N.Y. Acad. Sci.* 338:515-532.
- Sinclair, P.C. 1976. Vertical transport of desert particulates by dust devils and clear thermals. p. 497-526. *In* R.J. Engelmann and G.A. Sehmel (ed.) Atmosphere-surface exchange of particulate and gaseous pollutants. National Technical Information Service, CONF 740921, Richland, WA. 4-6 Sept. 1974. National Technical Information Service, Springfield, VA.
- Smith, R.M., P.C. Twiss, R.K. Krauss, and M.J. Brown. 1970. Dust deposition in relation to site, season, and climatic conditions. *Soil Sci. Soc. Am. Proc.* 34:112-117.
- Watson, A. 1979. Gypsum crusts in deserts. *J. Arid Environ.* 2:3-20.
- Young, J.A., and R.A. Evans. 1986. Erosion and deposition of fine sediments from playas. *J. Arid Environ.* 10:103-115.