

Solutes in Small Streams Draining Single Rock Types, Sangre de Cristo Range, New Mexico

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1535-F

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Water Resources Division
Surface Water Branch
Rm 2230





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By JOHN P. MILLER

GEOCHEMISTRY OF WATER

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UNITED STATES DEPARTMENT OF THE INTERIOR

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GEOCHEMISTRY OF WATER

SOLUTES IN SMALL STREAMS DRAINING SINGLE ROCK TYPES, SANGRE DE CRISTO RANGE, NEW MEXICO

By JOHN P. MILLER

ABSTRACT

The solute content of stream waters draining a single rock type was found to be essentially uniform regardless of the size of area drained. This implies a steady-state relation for the various weathering mechanisms through a considerable range in conditions of slope, soil, vegetation, and hydrology.

Average solute concentrations of waters draining quartzite, granite, and sandstone are in the proportion 1:2.5:10. Most of the solute content of waters draining sandstone is derived from carbonate cement and thin limestones, which together constitute less than 1 percent of the rock. Relative mobilities of the various elements (ratio of percentage in water to percentage in rock) agree generally with previous estimates based on less satisfactory data.

Calculated values for rates of chemical denudation suggest considerably greater importance of this factor in landscape sculpture than is commonly believed.

too general

INTRODUCTION

Weathering of rocks results in three kinds of products: (a) residual minerals, (b) authigenic minerals, and (c) solutes. The first two categories of materials are relatively immobile, except in the presence of vigorous transporting agencies, and tend to accumulate at the site of weathering. Soluble products, on the other hand, move readily with percolating ground waters and ultimately into the streams.

Investigations of weathering processes have consisted largely of chemical and mineralogical comparisons between unweathered rock and the overlying weathered mantle. Studies of weathering processes based primarily on composition of the soluble products are very few in number, despite the existence of a voluminous literature on water chemistry. A principal reason is that practically all regular sampling stations are at sites where stream waters draining several different rock types are mingled. This limitation of the available data led to the generalized conclusions of Smyth (1913) and Polynov (1937) about relative mobility of the common elements during weathering. In both cases, average compositions of diverse rocks were compared with average compositions of stream waters. Smyth's estimate applies to the entire surface of the earth, whereas Polynov considered only the surface underlain by igneous rocks. Recently, Anderson and

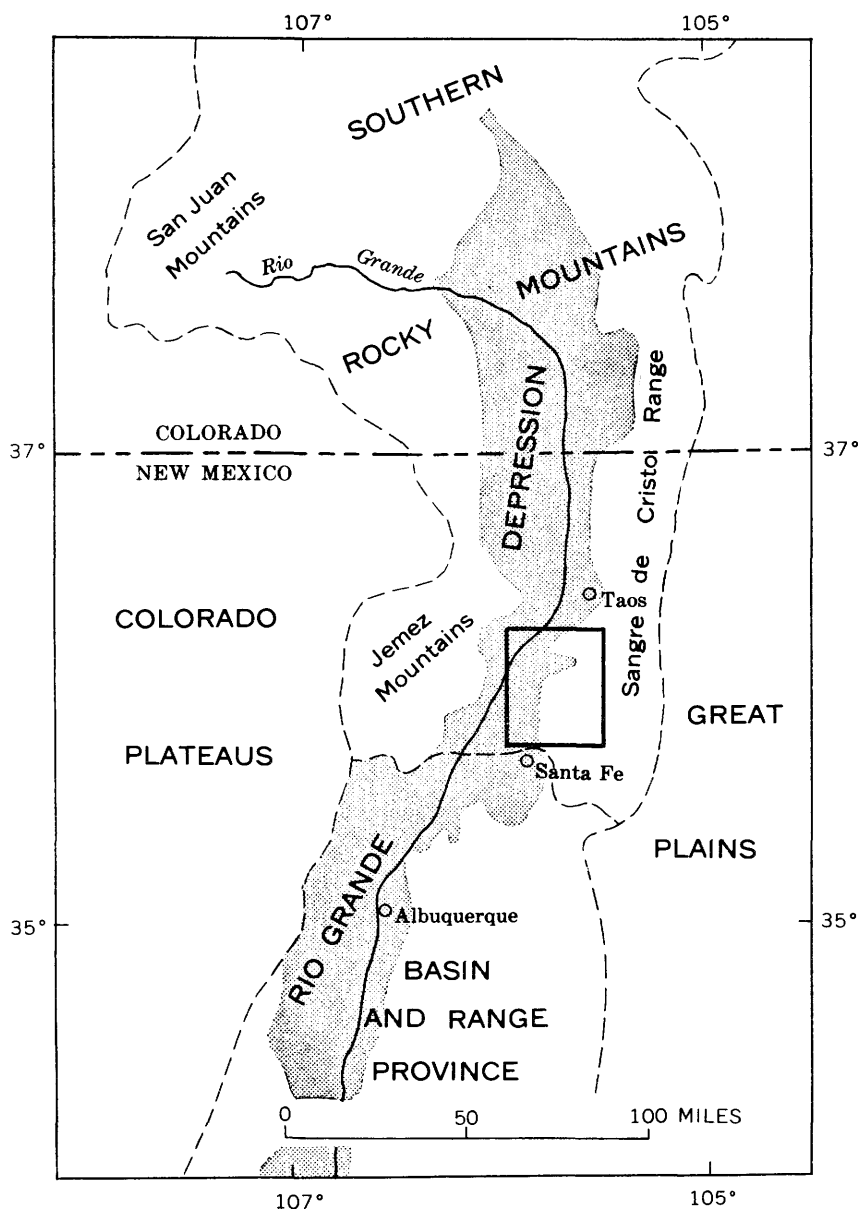


FIGURE 1.—Map showing location of study area in relation to regional physiographic features.

Hawkes (1958) have published estimates of relative mobility which apply to specific rock types in New England.

This paper describes the chemical character of stream waters derived from several small drainage basins, each of which is underlain

by one of three "uniform" rock types (granite, metaquartzite, and sandstone). Estimation of relative mobilities of the common elements and differences in chemical denudation rates between lithologic types were the primary objectives of this study.

ACKNOWLEDGMENTS

Cheerful assistance in the somewhat arduous task of sample collection was rendered by Dean Gerber, Santa Fe, N. Mex. Arthur Montgomery, Lafayette College, Pennsylvania, and P. K. Sutherland, University of Oklahoma, contributed unpublished information on mineralogical and chemical properties of rocks in the area studied and criticized the manuscript. The principal work of this study was done by the chemical analysts. To them, and also to other U.S. Geological Survey colleagues who aided in this project, special thanks are due. The suggestions of R. M. Garrels and R. Siever, Harvard University, at various stages of this investigation, are greatly appreciated.

PHYSICAL SETTING

The area studied in this report is located at the southern end of the Sangre de Cristo Range (fig. 1). The mountains rise 5,000 to 6,000 feet above the Rio Grande depression to the west and the Great Plains to the east, and reach a maximum elevation of 13,100 feet. Climate varies markedly with altitude. Average annual precipitation ranges from about 12 inches at the lower elevations to 35 inches or more on the highest peaks. Differences in precipitation and temperature are clearly indicated by zonation of vegetation. In order of their occurrence—from low altitude to high—pinon, yellow pine, aspen, spruce, and fir dominate the luxuriant forest which covers the mountains up to the timberline at 11,000 to 11,500 feet. Above timberline, there are clumps of dwarf trees and several kinds of sedges and grasses similar to varieties found in arctic regions.

STREAM CHARACTERISTICS

Streams in the southern Sangre de Cristo Range drain either to the Pecos River or to the Rio Grande. They flow in deep, narrow canyons, and the channels are covered with coarse gravels derived largely from adjacent valley walls. Runoff is characterized by a period of high discharges during the late-spring snowmelt season and by sporadic floods resulting from intense rainfall during summer and early fall. However, the streams never carry much suspended sediment. Even after heavy rains, they are merely cloudy rather than truly turbid.

Irrigation is widely practiced in this section of New Mexico, but all sampling stations discussed in this paper are more than a mile up-

stream from diversions. Most of the area considered is wilderness which, except for grazing of cattle and sheep and the presence of a few prospect pits, is unaffected by the activities of man.

A detailed account of stream characteristics in this part of the Sangre de Cristo Range has been published by Miller (1958).

SUMMARY OF GEOLOGY

A generalized geologic map and structure section, showing the major lithological and structural features, is given in figure 2. The oldest rocks of the Sangre de Cristo Range are Precambrian quartzites, schists, and granites, which underlie most of the mountain crest and are also exposed in several deep canyons of the Pecos drainage basin. A thick section of sedimentary rocks overlies this basement complex. Except for a thin (<100 feet) limestone of Mississippian(?) age, the entire sedimentary column is of Pennsylvanian age consisting in the areas where water samples were taken of several thousand feet of thick nonmarine sandstones alternating with shales and thin marine limestones.

Structurally, this part of the range is a broad north-trending anticline broken at several places by major faults that also trend roughly north. As can be seen in figure 2, the western flank of the anticline is greatly eroded and is buried by Tertiary sediments. Like the adjacent Picuris area (Montgomery, 1953), the Precambrian metamorphic rocks are complexly folded with axes trending roughly from east to west.

Pleistocene glaciation of the southern Sangre de Cristo Range consisted of numerous small valley glaciers, which produced rugged peaks and broad, deep cirques but left relatively little glacial and glaciofluvial debris in most valleys. Patterned ground, block fields, and other surficial features produced by Pleistocene and Recent frost action are abundant above 10,000 feet.

Chemical and mineralogical composition of rock types drained by the stream waters of the southern Sangre de Cristo Range are discussed under appropriate headings.

GRANITE

The granitic rocks of this area, referred to by Montgomery (1953) as the Embudo granite, include coarse-grained quartz monzonite, dark-biotite granite and light-colored, well-foliated granite, and also abundant pegmatites and quartz veins. Table 1 gives a chemical analysis and estimated mode of Embudo granite in the Picuris Range, which is a few miles north of the principal area considered here. According to Montgomery (written communication, November 1959), the Embudo granite is identical in both areas.

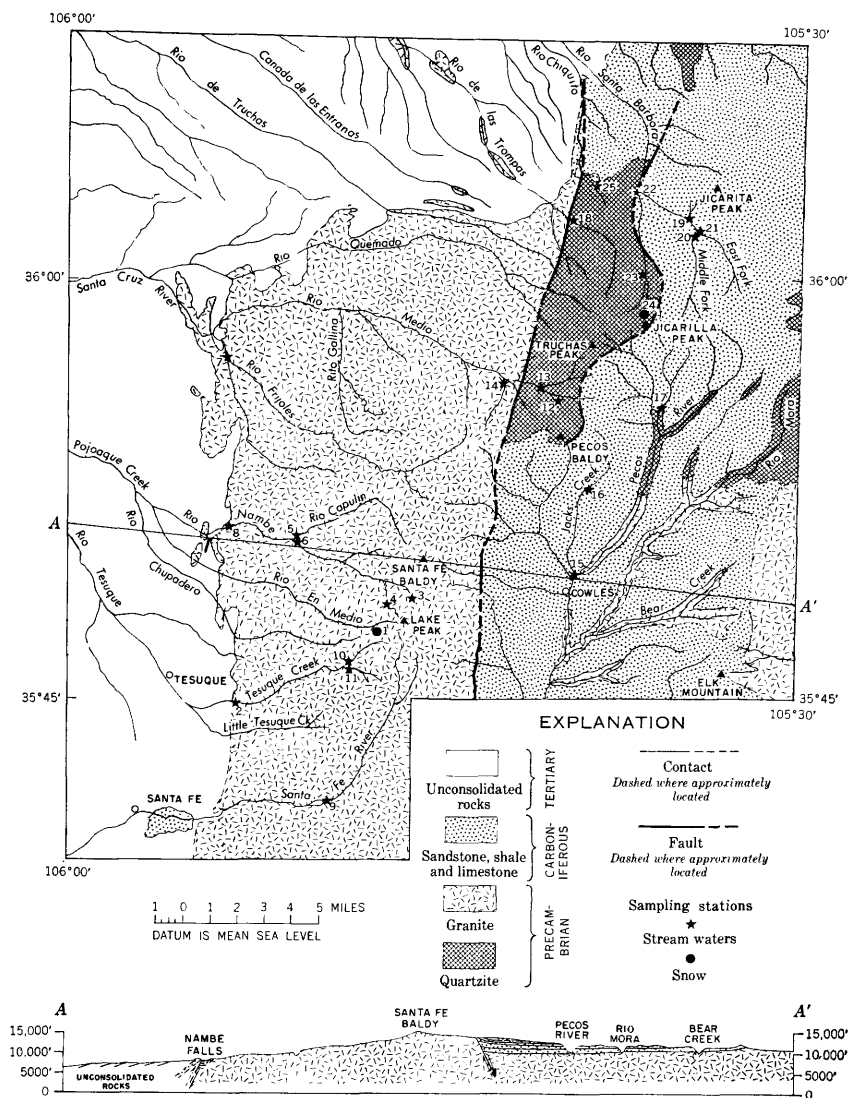


FIGURE 2.—Geologic map and structure section of study area showing points where stream waters and snow were sampled.

QUARTZITE

The metaquartzite considered in this study is the lower part of the Precambrian Ortega formation of Montgomery (1953). Although quartzite is the principal lithologic type in this formation, there are many thin interbedded layers of sillimanite-kyanite gneiss and also distinctive beds of several different schists, most of which, however,

TABLE 1. *Mode and chemical composition, in percent, of Embudo granite*

[Average of three analyses reported by Montgomery, 1953]

| Mode | | Chemical composition | |
|-----------------------------|-----|--------------------------------------|--------|
| Quartz----- | 30 | SiO ₂ ----- | 72. 12 |
| Microcline----- | 30 | TiO ₂ ----- | . 42 |
| Albite and oligoclase----- | 31 | Al ₂ O ₃ ----- | 14. 24 |
| Biotite----- | 6 | Fe ₂ O ₃ ----- | 1. 48 |
| Muscovite----- | 1 | FeO----- | . 99 |
| Epidote----- | 1 | MnO----- | . 09 |
| Sericite----- | 1 | MgO----- | . 52 |
| Chlorite----- | Tr. | CaO----- | 1. 56 |
| Magnetite and ilmenite----- | Tr. | Na ₂ O----- | 3. 17 |
| Sphene----- | Tr. | K ₂ O----- | 4. 03 |
| Apatite----- | Tr. | P ₂ O ₅ ----- | . 12 |
| Zircon----- | Tr. | S----- | . 01 |
| Allanite----- | Tr. | BaO----- | . 07 |
| Pyrite----- | Tr. | ZrO ₂ ----- | Tr. |
| | | CO ₂ ----- | . 03 |
| | | H ₂ O----- | . 77 |
| | | | 99. 62 |

do not occupy areas that drain to the streams considered in this report. The quartzite is many thousands of feet thick and dips steeply throughout the area.

Montgomery, who is making a detailed petrologic study of these rocks, prepared the mineralogical data given in table 2. No chemical analyses are available.

SANDSTONE

The rocks designated here as "sandstone" actually include also such diverse lithologic types as conglomerates, shales, mudstones, and thin limestones—all of Pennsylvanian age and up to 7,000 feet thick. In the area where water samples were taken, units called "limestone" in measured sections constitute 1 to 2 percent of the total thickness. However, the limestones are impure, and the CaCO₃ equivalent of the entire section, including calcareous cement in some of the terrigenous rocks, is 0.5 to 1.0 percent (P. K. Sutherland, written communication, November 1959). Roughly 25 percent of the total section is shale and mudstone. The remainder is a highly varied sequence of coarse terrigenous rocks (conglomerates, estimated 15 percent; sandstone, estimated 60 percent). Quartz and quartzite are the predominant detrital constituents, but feldspar and igneous and metamorphic rock fragments are present in small amounts throughout the sequence. In some layers, feldspathic constituents form a major proportion of the rock. Silica is the predominant cement, with carbonate minor in most beds.

TABLE 2.—*Estimated modes in percent of quartzite (Ortega formation) in areas draining to various sampling stations*

[Data from A. Montgomery, written communication]

| | Station 12 | Station 13 | Stations 18, 23, and 25 |
|-------------------------------|------------|----------------|----------------------------|
| Quartz..... | 97 | 89 | 97 |
| Muscovite..... | .5 | ¹ 2 | 1 |
| Biotite..... | .5 | 2 | ----- |
| Feldspar..... | ----- | 2 | ----- |
| Hornblende..... | ----- | 2 | ----- |
| Staurolite..... | .5 | ----- | ----- |
| Sillimanite..... | Tr. | 1 | .5 |
| Ilmenite and hematite..... | .5 | 1 | .5 |
| Epidote and clinozoisite..... | .1 | Tr. | .1 |
| Tourmaline..... | ----- | .3 | ----- |
| Garnet..... | Tr. | .2 | ----- |
| Kyanite..... | Tr. | .2 | ----- |
| Andalusite..... | Tr. | Tr. | ----- |
| Piedmontite..... | ----- | Tr. | ----- |
| Apatite..... | ----- | Tr. | ----- |
| Beryl..... | ----- | Tr. | ----- |
| Idocrase..... | ----- | Tr. | ----- |

¹ Biotite and chlorite.

Detailed chemical and mineralogical analyses of these rocks have not been made, and sampling them for the purpose of making detailed comparisons with water samples would be a major undertaking.

Throughout the area where water samples were collected, the sandstone sequence is flat lying or very gently dipping.

SAMPLING PROCEDURE

Altogether, 23 samples of stream waters were collected. The samples were distributed according to lithologic terrain of basin as follows: granite, 11; quartzite, 5; and sandstone, 7. In addition, two samples of snow were obtained, one each from granite and quartzite terrains. The total number of samples, and to some extent the location of sampling stations, was determined primarily by available time and manpower. In most cases, it was necessary to walk 5 to 15 miles and backpack the necessary equipment and the samples.

All water samples were collected between June 26 and July 8, 1958, except for sample 25 (taken July 26). This sampling period was chosen because it follows the peak snowmelt runoff and precedes the summer rains, which ordinarily begin during the first half of July. No rain fell during the month of June, but a few very small rains had occurred by July 26. At the time of sampling, all streams were at slightly less than half-bankfull stage.

The location of sampling stations is shown on figure 2. No special statistical sampling design was used. Rather, insofar as possible, the stations were arranged for each rock type so that samples from drainage areas of various sizes would be obtained. Although altitudes of sampling stations range from 6,700 feet to 10,400 feet, three-fourths of them are above 9,000 feet. Location and extent of rock exposure account for the considerable differences in altitude ranges of sampling stations on the three rock types:

| | <i>Altitude (feet)</i> |
|----------------|------------------------|
| Granite..... | 6, 700-10, 400 |
| Quartzite..... | 9, 400-10, 100 |
| Sandstone..... | 8, 300-10, 200 |

The procedure at each stream sampling station was as follows:

1. The pH of the water was determined by means of a portable pH meter. First, the meter was standardized with buffer solution, which previously had been brought to stream temperature. Next, water was dipped from the stream in a polyethylene beaker, the electrodes were immersed, and the pH was read. Two or more determinations were made at each station.

All field pH measurements are listed in table 3, to indicate degree of reproducibility of results. The field pH values listed in table 4 are averages of the data reported in table 3.

2. Two half-gallon samples were collected in polyethylene bottles at each station. Foreign matter (mostly spruce needles) was removed by filtration through a clean cotton handkerchief, which was thoroughly rinsed in the stream at each station. Cloth was used rather than filter paper because of the greater speed of filtration. The sample collected for spectrographic trace-element analysis was acidified to pH 6.0-6.5 with HCl; the other sample was not acidified or treated in any way prior to analysis.

The samples of snow were collected from snowfields above timberline. The surficial dust-covered snow was scraped away, and clean snow was ladled directly into polyethylene bottles with a silver spoon.

ANALYTICAL METHODS

All samples were analyzed by methods regularly used by the U.S. Geological Survey. Haffty (1960) has given a brief description of the residue method for spectrographic determination of trace elements in water.

It is exceedingly difficult to evaluate precision of the methods and accuracy of the results. From the discussion by Hem (1959), it appears that the precision for the common elements is ordinarily in the range 2 to 10 percent. However, in these dilute waters, concentrations of some elements are near the limits of sensitivity and the

TABLE 3.—*Values of all field pH measurements at various sampling stations*

| Station | pH | | | |
|---------------------------|-----|-----|-------|-------|
| Waters draining granite | | | | |
| 9----- | 7.0 | 7.0 | ----- | ----- |
| 11----- | 7.0 | 7.0 | 7.0 | ----- |
| 10----- | 7.1 | 7.2 | ----- | ----- |
| 2----- | 7.2 | 7.2 | 7.2 | ----- |
| 4----- | 7.0 | 7.0 | 7.0 | ----- |
| 3----- | 7.0 | 7.0 | 7.1 | 7.1 |
| 5----- | 7.2 | 7.2 | 7.2 | 7.2 |
| 6----- | 7.2 | 7.2 | 7.2 | 7.2 |
| 8----- | 7.2 | 7.1 | 7.1 | ----- |
| 14----- | 7.0 | 7.1 | ----- | ----- |
| 7----- | 7.2 | 7.3 | 7.4 | ----- |
| Waters draining quartzite | | | | |
| 12----- | 6.4 | 6.4 | ----- | ----- |
| 13----- | 6.6 | 6.7 | 6.7 | ----- |
| 18----- | 6.4 | 6.4 | 6.4 | ----- |
| 25----- | 6.6 | 6.6 | 6.8 | 6.8 |
| 23----- | 6.6 | 6.6 | ----- | ----- |
| Waters draining sandstone | | | | |
| 16----- | 8.0 | 8.0 | ----- | ----- |
| 15----- | 8.1 | 8.1 | ----- | ----- |
| 17----- | 8.1 | 8.2 | 8.2 | ----- |
| 19----- | 7.7 | 7.8 | ----- | ----- |
| 20----- | 7.8 | 7.8 | ----- | ----- |
| 21----- | 8.0 | 8.0 | ----- | ----- |
| 22----- | 8.0 | 8.0 | 8.2 | ----- |

results are probably somewhat less accurate. Precision of spectrographic methods is in the range 10 to 20 percent.

RESULTS OF ANALYSES

Complete results of chemical analyses for all samples are given in table 4.

Bicarbonate, sulfate, chloride, nitrate, calcium, magnesium, sodium, potassium, and silica were determined by standard chemical methods outlined by Rainwater and Thatcher (1960). Iron was determined both chemically and spectrographically. All other elements listed in table 4 were determined by emission spectroscopy. In addition, the following elements were sought but not detected in any of the spectrographic analyses: antimony, arsenic, bismuth, cadmium, cerium, cesium, dysprosium, erbium, europium, gadolinium, gallium, germanium, gold, hafnium, holmium, indium, iridium, lanthanum, lutetium, mercury, neodymium, niobium, osmium, palladium, phos-

TABLE 4.—*Chemical constituents of water samples*

[Results in parts per billion except as indicated]

| Sam- pling station | Location | Ali- tude (feet) | Drain- age area (sq mi) | Tem- pera- ture (°F) | pH | | Spec- ific con- duc- tance (micro- mhos at 25°C) | Dissolved solids | | Determined by chemical methods | | | | | | | | |
|--------------------------|----------------|------------------------|-------------------------------------|-------------------------------|-------|-----------------|--|--|--------|--------------------------------|----------------------|------------------------|---------------------|-----------------------|---|-------------------------------|-----------------------|-------------------------------|
| | | | | | Field | Labo- ratory | | Resi- due on evapo- ration at 180°C | Sum | Silica (SiO ₂) | Cal- cium (Ca) | Mag- nesium (Mg) | So- dium (Na) | Potas- sium (K) | Bicar- bonate (HCO ₃) | Sulfate (SO ₄) | Chlor- ide (Cl) | Nitrate (NO ₃) |
| | | | | | | | | | | | | | | | | | | |
| Snow samples | | | | | | | | | | | | | | | | | | |
| 1 | Lake Peak | 11,280 | (1) | 32 | --- | 6.1 | 5 | 4,000 | 3,000 | 2 n.d. | 300 | n.d. | 500 | 300 | 3,200 | n.d. | 200 | 100 |
| 24 | Jicarilla Peak | 11,500 | --- | 32 | --- | 5.3 | 5 | 5,000 | 2,000 | 100 | 200 | n.d. | 100 | 300 | 1,900 | n.d. | 200 | n.d. |
| | Average | --- | --- | --- | --- | --- | 5 | 4,500 | 2,500 | 50 | 250 | n.d. | 300 | 300 | 2,550 | n.d. | 200 | 50 |
| Waters draining granite | | | | | | | | | | | | | | | | | | |
| 9 | Santa Fe Creek | 7,950 | 15.3 | 59 | 7.0 | 6.7 | 38 | 34,000 | 29,000 | 9,300 | 3,700 | 900 | 2,100 | 700 | 16,000 | 4,300 | 200 | 200 |
| 11 | Rio Tesuque | 9,680 | .44 | 50 | 7.0 | 7.1 | 35 | 33,000 | 30,000 | 10,000 | 4,000 | 400 | 2,300 | 900 | 15,000 | 4,200 | 500 | 100 |
| 10 | do | 9,720 | 1.6 | 50 | 7.1 | 7.0 | 28 | 27,000 | 26,000 | 10,000 | 3,000 | 500 | 2,100 | 700 | 14,000 | 2,600 | n.d. | 100 |
| 2 | do | 7,400 | 8.3 | 61 | 7.2 | 7.0 | 43 | 38,000 | 32,000 | 11,000 | 3,700 | 1,100 | 2,500 | 800 | 20,000 | 2,900 | 400 | 200 |
| 4 | Rio Nambé | 10,370 | .52 | 50 | 7.0 | 6.7 | 22 | 20,000 | 15,000 | 3,500 | 2,800 | 200 | 1,900 | 400 | 10,000 | 2,900 | 200 | 200 |
| 3 | do | 10,390 | .88 | 46 | 7.0 | 6.7 | 25 | 23,000 | 21,000 | 6,900 | 3,000 | 300 | 1,500 | 400 | 11,000 | 2,900 | 200 | 200 |
| 5 | do | 7,670 | 11.4 | 55 | 7.2 | 6.8 | 35 | 33,000 | 28,000 | 10,000 | 3,700 | 500 | 2,200 | 300 | 16,000 | 3,400 | n.d. | 100 |
| 6 | do | 7,670 | 13.2 | 54 | 7.2 | 6.7 | 31 | 30,000 | 26,000 | 9,700 | 3,200 | 400 | 2,000 | 600 | 15,000 | 3,400 | 200 | 100 |
| 8 | do | 6,830 | 53.6 | 57 | 7.1 | 6.8 | 37 | 34,500 | 30,000 | 10,000 | 3,900 | 600 | 2,300 | 500 | 17,000 | 3,800 | 100 | 100 |
| 14 | Rio Santa Cruz | 9,200 | 2.0 | 50 | 7.0 | 6.9 | 38 | 35,000 | 30,000 | 10,000 | 4,200 | 600 | 2,400 | 500 | 16,000 | 4,800 | n.d. | 100 |
| 7 | do | 6,700 | 29.3 | 55 | 7.3 | 6.8 | 41 | 39,000 | 33,000 | 11,000 | 4,400 | 700 | 2,500 | 700 | 20,000 | 3,400 | 200 | 100 |
| | Average | --- | --- | --- | --- | --- | 34 | 31,400 | 27,300 | 9,200 | 3,600 | 560 | 2,070 | 620 | 15,450 | 3,280 | 180 | 110 |

Waters draining quartzite

| | | | | | | | | | | | | | | | | | | |
|----|-------------------|--------|-----|----|-----|-----|----|--------|--------|-------|-------|------|-----|-----|-------|-------|------|------|
| 12 | Rio Santa Cruz | 9,800 | 1.5 | 46 | 6.4 | 6.4 | 13 | 13,000 | 11,000 | 3,000 | 2,400 | n.d. | 400 | 300 | 5,100 | 2,400 | n.d. | 200 |
| 13 | do | 8,600 | 2.9 | 46 | 6.7 | 6.8 | 20 | 19,000 | 16,000 | 4,800 | 3,000 | n.d. | 800 | 400 | 8,200 | 3,000 | n.d. | 100 |
| 18 | Rio las Trampas | 8,400 | 3.1 | 41 | 6.4 | 6.2 | 15 | 15,000 | 11,000 | 3,800 | 1,800 | 200 | 900 | 300 | 3,100 | 1,900 | 200 | 200 |
| 23 | Rio Chiquito | 10,000 | 1.2 | 46 | 6.7 | 6.7 | 16 | 15,000 | 12,000 | 4,400 | 1,900 | n.d. | 900 | 300 | 6,600 | 1,000 | 100 | n.d. |
| 23 | Rio Santa Barbara | 10,100 | 1.2 | 50 | 6.6 | 6.2 | 9 | 10,000 | 6,000 | 2,000 | 1,900 | 100 | 200 | 200 | 3,300 | 500 | n.d. | 100 |
| | Average | | | | | | 15 | 14,400 | 11,200 | 3,600 | 1,920 | 60 | 520 | 300 | 5,700 | 1,760 | 60 | 120 |

Waters draining sandstone (with shale and thin limestone beds)

| | | | | | | | | | | | | | | | | | | |
|----|-------------------|--------|------|----|-----|-----|-----|---------|---------|-------|--------|-------|-------|-----|---------|--------|------|------|
| 16 | Pecos River | 10,000 | 2.8 | 46 | 8.0 | 7.9 | 130 | 96,000 | 90,000 | 4,800 | 31,000 | 700 | 800 | 400 | 91,000 | 7,300 | n.d. | 100 |
| 15 | do | 8,300 | 6.4 | 54 | 8.1 | 8.1 | 219 | 133,000 | 125,000 | 6,300 | 40,000 | 2,800 | 1,400 | 500 | 121,000 | 14,000 | 500 | 100 |
| 17 | do | 9,700 | 5.3 | 54 | 8.2 | 7.0 | 199 | 117,000 | 110,000 | 4,400 | 35,000 | 2,400 | 1,300 | 600 | 104,000 | 15,000 | 200 | n.d. |
| 19 | Rio Santa Barbara | 9,800 | 5.82 | 46 | 7.8 | 7.1 | 109 | 68,000 | 64,000 | 3,300 | 15,000 | 2,600 | 1,400 | 500 | 65,000 | 17,000 | 200 | 100 |
| 20 | do | 10,200 | 5.7 | 54 | 7.8 | 7.3 | 176 | 107,000 | 99,000 | 3,900 | 28,000 | 3,100 | 1,200 | 600 | 78,000 | 24,000 | 100 | 200 |
| 21 | do | 10,200 | 5.8 | 54 | 8.0 | 7.8 | 194 | 116,000 | 109,000 | 3,600 | 31,000 | 3,400 | 1,300 | 600 | 87,000 | 26,000 | 200 | 100 |
| 22 | do | 9,300 | 16.2 | 54 | 8.0 | 7.4 | 170 | 106,000 | 95,000 | 4,100 | 27,000 | 3,000 | 1,400 | 700 | 75,000 | 22,000 | n.d. | 200 |
| | Average | | | | | | 195 | 106,100 | 99,000 | 4,500 | 29,570 | 2,570 | 1,260 | 560 | 85,900 | 17,900 | 170 | 110 |

See footnotes at end of table.

TABLE 4.—*Chemical constituents of water samples—Continued*
 [Results in parts per billion except as indicated]

| Sam- pling station | Location | Determined by emission spectroscopy | | | | | | | | | | | | | | | | |
|--|----------------|-------------------------------------|---------------------|--------------------------|--------------|-----------------------|----------------|---------------------|--------------|--------------|----------------------|-----------------------------|------------------------------|----------------|-----------------------|----------------|------------------------|-----------------------|
| | | Alum- inum (Al) | Bar- ium (Ba) | Beryl- lithum (Be) | Boron (B) | Chro- mium (Cr) | Cobalt (Co) | Cop- per (Cu) | Iron (Fe) | Lead (Pb) | Lith- ium (Li) | Man- gane- se (Mn) | Mo- lyb- denum (Mo) | Nickel (Ni) | Rubid- ium (Rb) | Silver (Ag) | Stron- tium (Sr) | Titan- ium (Ti) |
| Snow samples | | | | | | | | | | | | | | | | | | |
| 1 24 | Lake Peak | | | | | | | | | | | | | | | | | |
| | Jicarilla Peak | | | | | | | | | | | | | | | | | |
| | Average | | | | | | | | | | | | | | | | | |
| Waters draining granite | | | | | | | | | | | | | | | | | | |
| 9 11 10 2 4 3 5 6 8 14 7 | Santa Fe Creek | 10 | 4 | n.d. | 5 | 5 | n.d. | 1 | 51 | 1 | 0.6 | 1 | n.d. | 0.3-3 | n.d. | 0.01 | 4 | 1 |
| | do | 4 | 6 | n.d. | 4 | 5 | n.d. | 3 | 12 | 4 | .7 | 2 | n.d. | .3-3 | .3 | n.d. | 5 | 3 |
| | do | 5 | 5 | n.d. | 3 | 10 | 0.03-0.3 | 3 | 57 | .6 | .6 | 2 | 0.3-3 | .3-3 | .3 | .02 | 5 | .4 |
| | do | 20 | 12 | n.d. | 7 | 3 | n.d. | 1 | 57 | 1.5 | 1 | 2 | 4-4 | .04-4 | .4 | .02 | 6 | .7 |
| | Rio Nambé | 22 | 5 | n.d. | 3 | 66 | .02-2 | 2 | 96 | 3 | 1 | 2 | 2-2 | 2-20 | n.d. | .03 | 8 | .6 |
| | do | 44 | 7 | 0.02-0.2 | 3 | 9 | n.d. | 4 | 53 | 2 | .5 | 2 | 2-2 | 2-2 | n.d. | .03 | 21 | .8 |
| | do | 11 | 12 | n.d. | 4 | 36 | .03-3 | 3 | 140 | 1 | 1 | 7 | 3-3 | 3-30 | n.d. | .03 | 22 | .6 |
| | do | 14 | 5 | n.d. | 3 | 7 | n.d. | 1 | 24 | .3 | 1 | 2 | .03-3 | .3-3 | .3 | .01 | 6 | .7 |
| | do | 17 | 8 | n.d. | 3 | 15 | .03-3 | 2 | 88 | .8 | 2 | 2 | 2 | 3-3 | .3-3 | .4 | 27 | 1 |
| | Rio Santa Cruz | 18 | 6 | n.d. | 3 | 5 | n.d. | 9 | 30 | 3 | 2 | 4 | 3-3 | .3-3 | .4 | .02 | 6 | 1 |
| | do | 16 | 11 | n.d. | 8 | 9 | n.d. | 2 | 39 | 1 | 2 | .7 | 4-4 | .4-4 | .4 | .01 | 15 | 1 |
| | Average | 16 | 7 | | 4 | 15 | | 2.5 | 59 | 1.2 | 1 | 2 | | | .2 | .02 | 11 | .8 |

Waters draining quartzite

| | | | | | | | | | | | | | | | | | | |
|----|------------------------|----|---|----------|----|---|----------|-----|----|-----|-------|---|-------|-------|-------|------|---|-----|
| 12 | Rio Santa Cruz..... | 14 | 5 | 0.01-0.1 | 10 | 5 | 0.01-0.1 | 2 | 18 | 1 | 0.5 | 2 | n.d. | 1-13 | n.d. | 0.02 | 2 | 0.2 |
| 13 | do..... | 17 | 8 | n.d. | 9 | 2 | n.d. | 1 | 13 | 1 | .4 | 2 | n.d. | .22 | n.d. | .01 | 4 | .2 |
| 18 | Rio de Trampas..... | 17 | 9 | .01-1 | 9 | 1 | .01-1 | 3 | 18 | 4 | ----- | 4 | n.d. | 1-7 | n.d. | .04 | 3 | .5 |
| 23 | Rio Chiquito..... | 15 | 8 | .01-1 | 1 | 6 | .01-1 | 2 | 59 | .5 | .4 | 4 | .01-1 | 1-15 | n.d. | .01 | 2 | .5 |
| 23 | Rio Santa Barbara..... | 17 | 9 | .01-1 | 9 | 1 | n.d. | 3 | 19 | .6 | ----- | 2 | n.d. | .1-1 | ----- | .03 | 2 | .4 |
| | Average..... | 12 | 8 | ----- | 6 | 3 | ----- | 2.3 | 25 | 1.3 | .4 | 2 | ----- | ----- | ----- | .02 | 3 | .4 |

Waters draining sandstone (with shale and thin limestone beds)

| | | | | | | | | | | | | | | | | | | |
|----|------------------------|----|----|-------|---|----|-------|-----|-----|-----|-----|-----|-------|-------|-------|-------|----|-----|
| 16 | Pecos River..... | 8 | 16 | n.d. | 4 | 6 | n.d. | 0.3 | 19 | 0.4 | 0.7 | 0.4 | n.d. | 0.1-1 | n.d. | n.d. | 33 | 0.9 |
| 17 | do..... | 24 | 24 | n.d. | 5 | 2 | n.d. | .4 | 11 | 1.6 | 1 | 1.5 | n.d. | n.d. | n.d. | n.d. | 89 | 1 |
| 18 | do..... | 40 | 21 | n.d. | 5 | 2 | n.d. | .2 | 32 | 1 | 1 | 1 | n.d. | n.d. | n.d. | n.d. | 90 | 4 |
| 19 | do..... | 31 | 28 | n.d. | 5 | 5 | n.d. | .7 | 24 | 2 | 1 | 1 | n.d. | n.d. | n.d. | .04 | 25 | 2 |
| 20 | Rio Santa Barbara..... | 34 | 31 | n.d. | 6 | 4 | n.d. | .4 | 72 | 2.7 | 1 | 1 | n.d. | .7-7 | n.d. | n.d. | 57 | 3 |
| 21 | do..... | 5 | 35 | n.d. | 4 | 5 | n.d. | .2 | 26 | 1 | 2 | 1 | n.d. | .1-1 | n.d. | n.d. | 46 | 2 |
| 22 | do..... | 44 | 33 | n.d. | 7 | 33 | .1-1 | 1 | 230 | 2 | 1 | 4 | n.d. | 1-10 | n.d. | n.d. | 59 | 5 |
| | Average..... | 28 | 27 | ----- | 5 | 8 | ----- | .5 | 59 | 1.3 | 1.1 | 1.3 | ----- | ----- | ----- | ----- | 57 | 2.5 |

¹ Leaders (-----), not determined. ² n.d., not detected. ³ Determined by chemical method.

phorus, platinum, praseodymium, rhenium, rhodium, ruthenium, samarium, scandium, tantalum, tellurium, terbium, thallium, thorium, thulium, tin, tungsten, uranium, vanadium, ytterbium, yttrium, zinc, and zirconium.

Values of pH measured in the laboratory (at $\approx 25^{\circ}\text{C}$) are consistently lower than those measured in the field (at stream temperature). The differences are attributable in part to the higher temperature of the laboratory and probably also to changes in the gaseous CO_2 content of the water in the laboratory environment. Both sets of data show that waters draining sandstone are alkaline (pH is more than 7.0); those from granite are approximately neutral (pH 6.7–7.3); and those from quartzite are acid (pH is less than 7.0).

Dissolved-solids determinations by the residue-on-evaporation method and by calculation (sum) should be approximately equal, and comparison of these two quantities provides a rough check on the accuracy and completeness of the analysis. A detailed discussion of the two methods is given by Rainwater and Thatcher (1960, p. 269–272). Average values for dissolved solids determined by the residue-on-evaporation method exceed those obtained by calculation by 15 percent for granite waters, about 30 percent for quartzite waters, and 7 percent for sandstone waters.

The data for one of the snow samples (No. 24) indicate either an error in determination of some constituent or possibly presence of foreign material in the residue (dissolved solids). Sample 23 is anomalous, compared with other quartzite waters, but values of specific conductance indicate that reported compositional differences are not related to analytical errors.

It is apparent from table 4 that concentrations of solutes in waters from each rock type are fairly uniform regardless of drainage area above the sampling station. Therefore, the data for samples from each type can be averaged (table 5). Average concentrations of waters draining quartzite, granite, and sandstone are in the proportion 1:2.5:10 respectively.

Geological Survey data for miscellaneous samples collected during the first half of July 1957 at sites draining a single rock type in this area compare very closely with results given in table 4. This statement applies particularly to dissolved solids and pH, as the analyses are incomplete for some constituents.

SOLUTES IN SNOW

Because only two samples of snow were analyzed, and with rather disparate results, few conclusions can be drawn. Bicarbonate is the most abundant dissolved constituent and comprises roughly two-thirds of the total. However, S. M. Rogers (written communication

SOLUTES IN SMALL STREAMS DRAINING SINGLE ROCK TYPES F-15

TABLE 5.—Average percentage composition of dissolved constituents in snow and stream waters draining various rock types

[Number of samples averaged in each category is shown in parentheses]

| Constituent | Snow (2) | Granite (11) | Quartzite (6) | Sandstone (7) |
|--------------------------------|-----------------|-----------------|------------------|------------------|
| Bicarbonate (HCO_3) | 68.8 | 51.0 | 46.7 | 61.2 |
| Sulfate (SO_4) | | 10.8 | 14.4 | 12.7 |
| Nitrate (NO_3) | 1.3 | .4 | 1.0 | .1 |
| Chloride (Cl) | 5.4 | .6 | .5 | .1 |
| Silica (SiO_2) | .7 | 14.2 | 13.8 | 1.5 |
| Aluminum (Al) | | .05 | .1 | .02 |
| Magnesium (Mg) | | 1.8 | .5 | 1.8 |
| Calcium (Ca) | 6.8 | 11.9 | 15.8 | 21.1 |
| Strontium (Sr) | | .04 | .03 | .04 |
| Barium (Ba) | | .02 | .07 | .02 |
| Sodium (Na) | 8.1 | 6.8 | 4.3 | .9 |
| Potassium (K) | 8.1 | 2.0 | 2.5 | .4 |
| Rubidium (Rb) | | .001 | (¹) | (¹) |
| Lithium (Li) | | .003 | .003 | .001 |
| Iron (Fe) | ² .8 | .2 | .2 | .04 |
| Titanium (Ti) | | .003 | .003 | .002 |
| Boron (B) | | .01 | .05 | .004 |
| Lead (Pb) | | .004 | .01 | .001 |
| Chromium (Cr) | | .05 | .03 | .01 |
| Manganese (Mn) | | .01 | .02 | .001 |
| Copper (Cu) | | .01 | .02 | n.d. |
| Silver (Ag) | | .0001 | .0002 | n.d. |
| Total | 100.0 | 99.90 | 100.04 | 99.94 |

¹ Not determined.

² Determined colorimetrically (bipyridine method); other values for iron were determined spectrographically.

June 18, 1959) found that 56 samples of snow, mostly from the Sierra Nevada, ranged in bicarbonate content from 0 to 75 percent and averaged 48 percent.

The analyses of Sangre de Cristo snow are compared in the following table with the data for rain in the same area, using values for rain

| | Rain (ppm) | Snow (ppm) |
|---------------|---------------|---------------|
| Cl | 0.2-0.3 | 0.2 |
| SO_4 | 3.0-4.0 | .0 |
| Na | .2- .3 | .3 |
| K | .1- .2 | .3 |
| Ca | 3.0-3.5 | .2 |

taken from maps showing isopleths of concentration presented by Junge and Werby (1958). Except for calcium and sulfate, the agreement is good. Junge and Werby consider dust storms to be the principal source of calcium, and decomposition of organic matter the major source of sulfate in rain. Both of these should be less important at high altitudes and especially during winter.

SPECIFIC IONS IN STREAM WATERS

Bicarbonate is by far the most abundant dissolved constituent in waters from all three rock types. Solution of intergranular carbonate cement and thin limestone beds accounts for the high concentrations in sandstone waters. The bicarbonate content of quartzite and granite waters must be derived mostly from atmospheric and pedogenic sources.

Sulfate concentrations of sandstone waters are 6 to 10 times those of granite and quartzite waters. The atmospheric contribution is unknown. Oxidation of trace amounts of pyrite is the only known mineral source of sulfate for granite and quartzite waters. Similarities in composition of snow and waters from all three rock types indicate that both nitrate and chloride are mostly of atmospheric origin.

Iron concentrations are not easily interpreted. The value for sample 22 (see table 4) probably is too high, but if it is accepted, then average differences between waters draining various rock types are roughly twofold. Difficulties in determination of iron are indicated by table 6, which compares the results of colorimetric (bipyridine method) and spectrographic analyses. Colorimetric values are notably lower for 21 of the 23 samples, and the exceptions are both granite waters. Both methods give approximately the same average concentration of iron in granite waters. Averages for quartzite and sandstone waters are 6-fold and 20-fold greater, respectively, by the spectrographic method. These results undoubtedly reflect changes undergone by the samples after collection as well as effects of differences in analytical techniques.

Titanium concentrations are 3 to 6 times greater in sandstone waters than granite and quartzite waters. Ilmenite, magnetite, and sphene are the only likely sources of titanium, but those minerals are generally believed to be very insoluble.

Chromium values for samples 4, 5, and 21 (see table 4) are higher by an order of several magnitudes than concentrations in other samples. Whether these differences are real or the result of errors in analysis is not known.

RELATIVE MOBILITY OF THE ELEMENTS

The stream waters described in this report were derived entirely from snowmelt that had percolated through thin surficial deposits and underlying bedrock. Traveltime of meltwater from snowbank to stream did not exceed 3 months and probably was much less. Despite great differences in altitude, slope, vegetation, drainage area, -

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TABLE 6.—*Iron analysis, in parts per million, by two methods*

[Samples are listed in same order as in table 3]

| Sampling station | Spectrographic | Colorimetric ¹ |
|-------------------------|----------------|---------------------------|
| Granite waters | | |
| 9----- | 0. 051 | 0. 04 |
| 11----- | . 012 | . 00 |
| 10----- | . 057 | . 22 |
| 2----- | . 057 | . 11 |
| 4----- | . 096 | . 01 |
| 3----- | . 053 | . 00 |
| 5----- | . 14 | . 04 |
| 6----- | . 024 | . 02 |
| 8----- | . 088 | . 02 |
| 14----- | . 030 | . 00 |
| 7----- | . 039 | . 03 |
| Quartzite waters | | |
| 12----- | 0. 018 | 0. 00 |
| 13----- | . 013 | . 00 |
| 18----- | . 018 | . 01 |
| 25----- | . 059 | . 01 |
| 23----- | . 019 | . 00 |
| Sandstone waters | | |
| 16----- | 0. 019 | 0. 01 |
| 15----- | . 011 | . 00 |
| 17----- | . 032 | . 00 |
| 19----- | . 024 | . 00 |
| 20----- | . 072 | . 00 |
| 21----- | . 026 | . 01 |
| 22----- | . 23 | . 00 |

¹ Bipyridine method.

and runoff conditions, waters draining a specific rock type are remarkably uniform in composition. This relation, shown in figure 3, implies that solute concentration is the result of weathering processes operating at uniform intensity and presumably under steady-state conditions over broad areas. Thus, different basins draining the rock of the same type yield waters of similar composition provided there is no dilution of ground waters by water flowing overland directly into channels. Also, because stream flow is several times faster than subsurface flow, the solute content must be acquired by the water before it reaches the channels. Therefore, the concentrations of various elements in these waters may be considered the result of differences in mobility under the prevailing conditions of weathering.

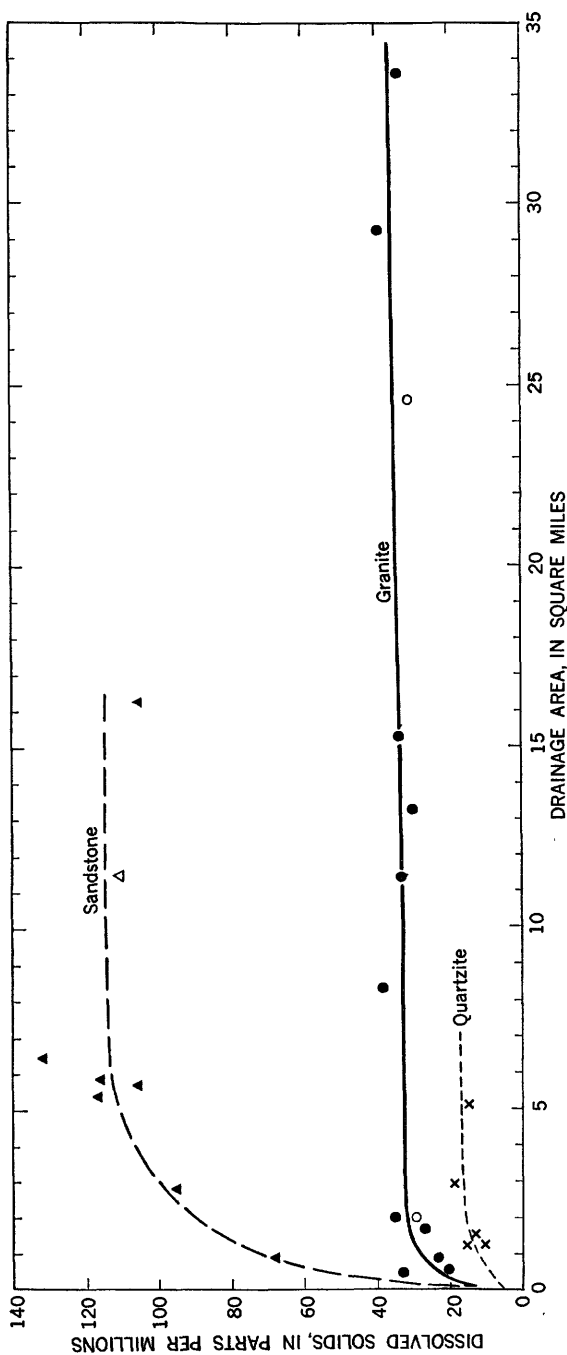


FIGURE 3.—Relation of dissolved solids to drainage area, showing approximate uniformity of waters derived from rock of each type. Open circles and triangles represent weighed-mean values for locations below tributary junctions; that is, data for station pairs (5 and 6, 10 and 11, 20 and 21) were combined by weighting according to prevailing discharge of each tributary at time of sampling. Each curve intersects the y -axis at the average value of dissolved solids in snow (≈ 5 ppm).

Previous workers (Smyth, 1913; Polynov, 1937; Anderson and Hawkes, 1958) have defined the ratio

$$\frac{\text{Percent of element in water}}{\text{Percent of element in rock}} = \text{relative mobility,}$$

and this designation is used here also. Data on chemical composition of the Embudo granite of Montgomery (1953) of the Sangre de Cristo Range are adequate for reasonably accurate calculation of relative mobilities. In the case of quartzite and sandstone, estimated chemical compositions, computed from modes, permit only comparison of order of mobility.

Calculated values of relative mobilities are given in table 7. The order of mobility for the various rocks can be summarized as follows:

Granite-----Ca>Mg>Na>Ba>K>Si>Fe=Mn>Ti>Al

Quartzite....Ca>>Na>>K>Mg>Fe>Si>Al

Sandstone...Ca>>>Na>K>Si=Al

For granite, the order and also specific values agree reasonably well with previous work, except for the finding of Anderson and Hawkes (1958) that magnesium is the most mobile element of certain New England granites. Comparative data for the other rocks are not available.

The exceedingly large values for relative mobility of calcium in quartzite and sandstone serve to emphasize the variety of factors affecting the ratio. In particular, the proportion of relatively inert minerals present in a rock may tend to obscure significant relations between highly reactive constituents present in small quantities. Further consideration of relative mobility should include analyses of soil waters and also laboratory determination of solubilities both for bulk rock and for its individual constituent minerals.

RATE OF CHEMICAL DENUDATION

The yield of dissolved products from a basin is commonly expressed as a denudation rate, meaning the average rate of lowering of the land surface. Accurate determinations require more detailed hydrologic and chemical information than is available for most areas. Estimation of denudation rates from the Sangre de Cristo data involves the following assumptions.

1. Average concentrations of dissolved solids reported for waters derived from each rock will be considered as mean annual values. Because of low-flow conditions at the time of sampling, they may be closer to maximum annual concentrations; but specific data on this point are lacking. However, study by C. H. Hembree and F. H. Rainwater (written communication, Jan. 22, 1960) of waters derived

TABLE 7.—Composition of dissolved constituents in waters compared with composition in source rocks, and calculated relative mobilities of various constituents

[Values are recalculated to 100 percent]

| Constituent | Source | Granite | | Quartzite | | Sandstone | |
|-----------------------|-------------------------|----------------|-------------------|------------------|-------------------|-------------------|-------------------|
| | | Percent | Relative mobility | Percent | Relative mobility | Percent | Relative mobility |
| Si..... | Water..... Rock..... | 38.24 87.30 | 0.57 | { 37.09 ≈95 } | ≈0.4 | { 5.95 ≈96 } | ≈0.06 |
| Al..... | Water..... Rock..... | .14 15.07 | | { .26 ≈2 } | | { .08 ≈1 } | |
| Mg..... | Water..... Rock..... | 4.98 .62 | 8.03 | { 1.32 ≈.3 } | ≈4 | { 7.08 } | |
| Ca..... | Water..... Rock..... | 32.01 2.22 | | { 42.38 ≈.2 } | | { 81.48 ≈.4 } | |
| Ba ¹ | Water..... Rock..... | .16 .12 | 1.33 | { .24 } | | { .23 } | |
| Na..... | Water..... Rock..... | 18.41 4.70 | | { 11.49 ≈.2 } | | { 3.47 ≈.8 } | |
| K..... | Water..... Rock..... | 5.51 5.70 | .96 | { 6.62 ≈1 } | ≈7 | { 1.54 ≈.9 } | ≈2 |
| Fe..... | Water..... Rock..... | .52 3.62 | | { .55 ≈1 } | | { .16 } | |
| Ti..... | Water..... Rock..... | .01 .50 | .02 | { .01 ≈.2 } | ≈.05 | { .01 } | |
| Mn..... | Water..... Rock..... | .02 .14 | | { .04 ≈.02 } | | { .003 } | |

¹ Includes Sr.

from granite in the Wind River Range, Wyo., indicates that concentration at any given station changes very slightly with variation in discharge. Furthermore, as in the present study, their data show that concentration is independent of drainage area.

TABLE 8.—Runoff data for gaging stations in the Sangre de Cristo Range

| Stream and location | Altitude (feet) | Drainage area (sq mi) | Average annual discharge (cfs per sq mi) | Average annual runoff (inches) | Years of record | Length of record (years) |
|-----------------------------------|--------------------|--------------------------|--|---|---------------------------------|--------------------------------|
| Rio Tesuque near Santa Fe..... | 7, 100 | 11 | 0.29 | 3.9 | 1936-50 | 15 |
| Rio Nambe near Nambe..... | 6, 200 | 37 | .29 | 3.9 | 1933-40, 1942-50 | 17 |
| Santa Cruz River at Cundiyo..... | 6, 460 | 86 | .37 | 5.0 | 1931-57 | 27 |
| Pecos River near Pecos..... | 7, 505 | 189 | .51 | 6.9 | 1931-57 | 27 |
| Santa Fe River near Santa Fe..... | 7, 718 | 18 | .46 | 6.2 | 1913-18, 1919-27, 1928-57 | 42 |
| Rio Santa Barbara near Llano..... | 8, 300 | 38 | .77 | 10.4 | 1953-57 | 5 |

2. The linear increase of precipitation and runoff with altitude, indicated by station data, is extrapolated to the crest of the range. Available data on runoff in the southern Sangre de Cristo Range, summarized in table 8, are from stations fairly well distributed through the altitude range 6,200 to 8,300 feet. Precipitation data given in the Climatic Summary of the United States to 1930 (U.S. Department of Agriculture) consist of records of more than 10 years duration for 11 stations ranging in altitude from 6,000 to 9,000 feet.

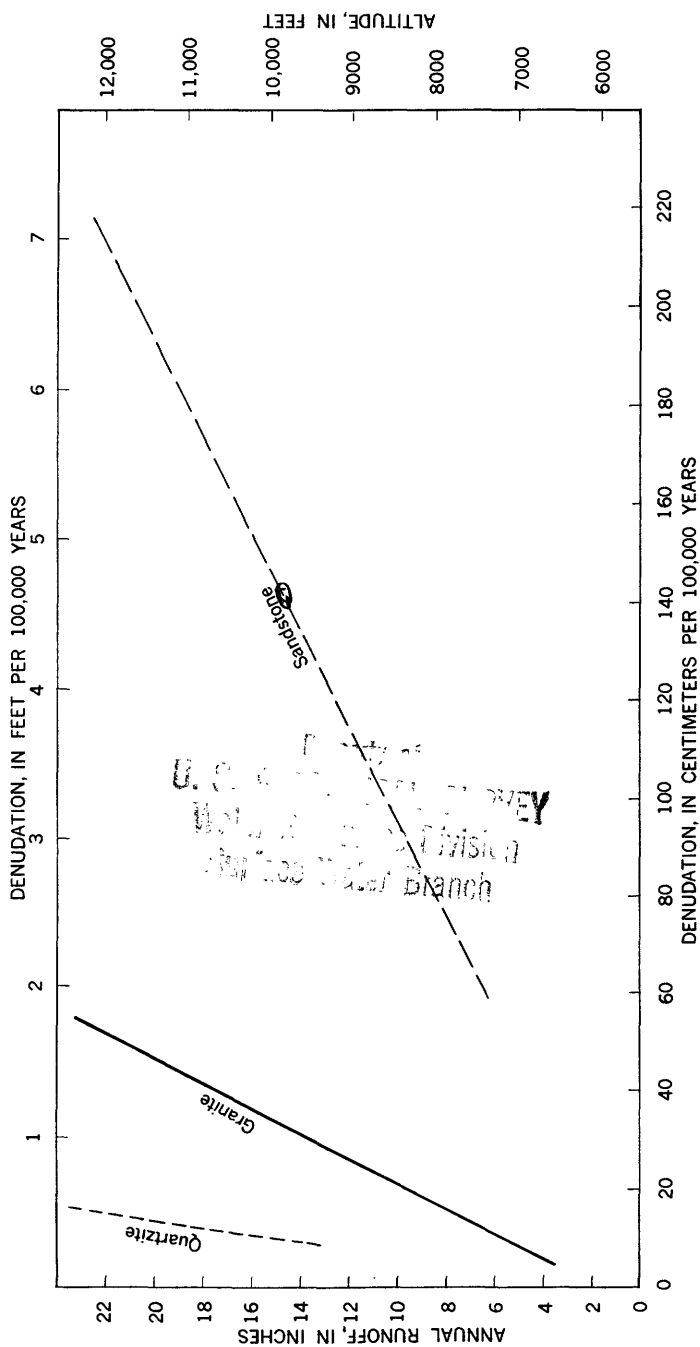
3. The data for snow (table 4) and the results of Junge and Werby (1958) indicate that the approximate average concentration of precipitation in this area is 5 ppm of dissolved solids. In order to correct values of dissolved solids in stream waters, the average atmospheric contribution must first be weighted according to the ratio of precipitation to runoff. Altitudinal variation in this correction, assuming 5 ppm dissolved solids in precipitation, is given below.

| <i>Altitude (feet)</i> | <i>Precipitation (inches)</i> | <i>Runoff (inches)</i> | <i>Ratio</i> | <i>Correction (ppm)</i> |
|----------------------------|-----------------------------------|----------------------------|--------------|-----------------------------|
| 7,000----- | 13.3 | 5.0 | 2.7 | -13 |
| 8,000----- | 17.5 | 8.6 | 2.0 | -10 |
| 9,000----- | 21.7 | 12.0 | 1.8 | -9 |
| 10,000----- | 25.9 | 15.5 | 1.7 | -8 |
| 11,000----- | 30.1 | 19.0 | 1.6 | -8 |
| 12,000----- | 34.3 | 22.4 | 1.5 | -7 |

Quartzite terrains in this area are restricted to high altitudes, but granite and sandstone extend from the base of the range to the crest.

4. Specific gravity of all three rock types is considered to be 2.6. Calculated values of denudation rates are plotted in figure 4. These results emphasize that denudation depends both on the chemical susceptibility of the rock to weathering and on the total quantity of solvent, which in this case is closely related to altitude. In general, these streams carry very little suspended load, and it may be that downwearing by chemical denudation is a major process of landscape sculpture in mountainous regions.

Assuming that these estimates of denudation rates are reasonably accurate, it seems very unlikely that erosion surfaces can be preserved unaltered for millions of years. For example, the curves of figure 4 indicate that 1 million years of weathering at 10,000 feet could cause sandstone terrains to be lowered 48 feet, granite terrains by 11 feet, and meta-quartzite terrains by 3 feet. Thus, solution weathering alone would considerably lower any surface and in lithologically contrasting areas would produce rugged relief within a few million years.



F —Calculated rates of chemical denudation, showing differences between rock types and variation with altitude.

CONCLUSIONS

The approximately uniform concentration of solutes in waters draining a single rock type indicate a steady-state relation for various weathering mechanisms affecting the system rock-water. This generalization applies for a considerable range in conditions of slope, soil, vegetation, and hydrology. Such a relation appears to be potentially useful for predicting the chemical character of composite waters derived from several rock types.

Estimated values of denudation rates indicate that solution weathering deserves greater consideration in several kinds of geomorphic problems.

Future investigations of the kind described here should be expanded to include experimental determinations of rock and mineral solubilities.

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