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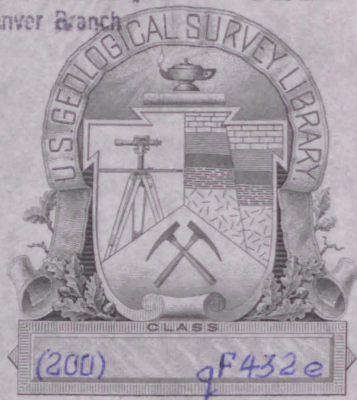
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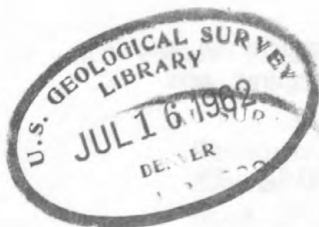
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UNITED STATES
DEPARTMENT OF THE INTERIOR
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ANNOUNCEMENT OF WATER-RESOURCES REPORTS RELEASED FOR PUBLIC INSPECTION

The Geological Survey announces that the following reports on water resources in the various sections of the country are being released in open file. Copies of most of the reports are available for consultation in the room indicated, General Services Building, Washington 25, D.C. Some of them also are available for consultation at other places as listed. Copies are not available for distribution.

1. Geology and ground-water resources of the Athens area, Alabama, by W. M. McMaster. 77 p., 10 pls., 6 figs.

Geological Survey, Oil and Gas Board Bldg., University of Alabama,
Tuscaloosa, Ala.

Office of the Mayor, Athens, Ala.

Room 1242-G, GSA Bldg.

2. Preliminary report on ground-water conditions at Homer, Alaska, by R. M. Waller. 15 p.

Geological Survey, Room 501, Cordova Bldg., 555 Cordova Street,
Anchorage, Alaska

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3. Well records, depth-to-water measurements and logs of selected wells and test holes, and chemical analyses of ground water in the Arkansas Valley region, Arkansas, by R. M. Cordova. 233 p., 5 figs.

Geological Survey, Room 2301, Federal Office Bldg., 700 West Capitol Avenue,
Little Rock, Ark.

Room 1242-G, GSA Bldg.

4. Map showing land subsidence in the Tulare-Wasco area, California, 1959-62, by B. E. Lofgren.

Geological Survey, Room 8024, Federal Bldg. and U.S. Court House,
650 Capitol Avenue, Sacramento, Calif.

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5. Physical and hydrologic properties of water-bearing deposits in the Los Banos-Kettleman City area, California, by A. I. Johnson and D. A. Morris. 179 p., 26 figs.

Geological Survey, Hydrologic Laboratory, Room 1775, Bldg. 25,
Denver Federal Center, Denver, Colo.
Geological Survey, Room 8024, Federal Bldg. and U.S. Court House,
650 Capitol Avenue, Sacramento, Calif.
Room 1242-G, GSA Bldg.
6. Ground-water resources of southern New Castle County, Delaware,
by D. R. Rima, O. J. Coskery, and P. W. Anderson. 117 p., 22 figs.

Delaware Geological Survey, University of Delaware, Newark, Del.
Room 1242-G, GSA Bldg.
7. Water levels in Delaware in 1961, by O. J. Coskery. 46 p., 3 figs.

Delaware Geological Survey, University of Delaware, Newark, Del.
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8. Ground-water resources of Collier County, Florida, by H. J. McCoy.
98 p., 29 figs.

Geological Survey, Gunter Bldg., Tennessee and Woodward Streets,
Tallahassee, Fla.
State Geological Survey, Tallahassee, Fla.
Room 1242-G, GSA Bldg.
9. Ground-water records of Flagler, Putnam, and St. Johns Counties, Florida,
by B. J. Bermes, G. W. Leve, and G. R. Tarver. 19 p., 5 figs.

Geological Survey, Gunter Bldg., Tennessee and Woodward Streets,
Tallahassee, Fla.
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10. Geology and ground-water resources of the Paleozoic rock area,
Chattooga County, Georgia, by C. W. Cressler. 41 p., 2 figs.

Geological Survey, Room 416, 19 Hunter Street, SW., Atlanta, Ga.
Room 1242-G, GSA Bldg.
11. Water supply for a fish-hatchery site, Clearwater Valley, Idaho,
by M. J. Mundorff and W. I. Travis. 36 p., 12 figs.

Geological Survey, Room 205, 914 Jefferson Street, Boise, Idaho
Room 1242-G, GSA Bldg.

12. Feasibility of artificial recharge in the Snake River basin, Idaho, by M. J. Mundorff. 98 p., 48 figs.

Geological Survey, Room 205, 914 Jefferson Street, Boise, Idaho
Bureau of Reclamation, 214 Broadway, Boise, Idaho
Room 1242-G, GSA Bldg.

13. Ground-water resources of west-central Indiana--Preliminary report, Montgomery County, by F. A. Watkins, Jr., and D. G. Jordan. 110 p., 3 pls., 2 figs.

Geological Survey, Room 407, 611 North Park Avenue, Indianapolis, Ind.
Indiana Department of Conservation, Indiana State Office Bldg.,
100 North Senate Avenue, Indianapolis, Ind.
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14. Ground-water resources of west-central Indiana--Preliminary report, Fountain County, by F. A. Watkins, Jr., and D. G. Jordan. 101 p., 3 pls., 2 figs.

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15. Ground-water resources of west-central Indiana--Preliminary report, Vermillion County, by F. A. Watkins, Jr., and D. G. Jordan. 88 p., 2 pls., 2 figs.

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17. Reconnaissance of ground-water conditions in the Duluth Municipal Airport area, Minnesota, by J. E. Rogers. 18 p., 2 figs.

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Nye County, Nevada, by G. E. Walker. 48 p., 11 figs.

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Nevada, by M. S. Garber and William Thordarson. 74 p., 5 figs.

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20. Development of the ground-water resources of St. Croix, Virgin Islands,
by G. E. Hendrickson. 84 p., 1 fig.

Geological Survey, 1209 Avenida Fernández Juncos, Santurce, P.R.
Department of Public Works, Christiansted, St. Croix, V.I.
Room 1242-G, GSA Bldg.

- ✓ 21. Empirical studies of water from "monolithologic terranes,"
by J. H. Feth. 39 p., 11 figs.

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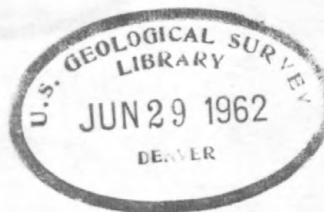
DATE: June 26, 1962

FROM : J. H. Feth, GW Branch, WRD, Menlo Park, Calif.

SUBJECT: PUBLICATIONS - Open-file release of "Empirical Studies of
Water from Monolithologic Terranes,"
by J. H. Feth.

Enclosed is carbon copy of the open-file report named
above. This report was recommended for open file by
the Director on May 17, 1962.

J. H. Feth
J. H. Feth
Geologist *(mg)*

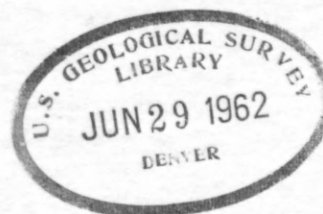


Enclosure

U.S.G.S. Water Resources Division
Press release dated June 27, 1962.

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EMPIRICAL STUDIES OF WATER FROM "MONOLITHOLOGIC" TERRANES



By J. H. Feth, Menlo Park, California

U.S. Geological Survey
OPEN FILE REPORT

This report is preliminary and has not been edited or reviewed for conformity with Geological Survey standards.

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EMPIRICAL STUDIES OF WATER FROM "MONOLITHOLOGIC TERRANES"

By

J. H. Feth

ABSTRACT

The chemical relationship between rocks and the water moving through them has been studied relatively little. This report considers these relations with reference to granitic, basaltic, and carbonate-rock terranes. The term "monolithologic terrane" is used in the sense of a body of rock of essentially homogeneous lithology and of sufficient extent to receive, store, and transmit water to springs or wells.

Review of the rather scanty literature in the field suggests that waters from carbonate-rock aquifers are distinguishable by their high percentages of calcium and of bicarbonate. In waters derived from igneous rocks the major cations--calcium, magnesium, and sodium--tend to be more nearly equivalent and silica characteristically makes up a large percentage of the dissolved-solids contents of the waters, reaching 30 or 35 percent of the total in some. Neither the earlier studies, however, nor those here reported have produced consistently reliable devices by which the lithology of the aquifer can be recognized from the reported chemical analyses of the water.

In all, analyses of 100 waters from granitic rocks, 75 from basaltic rocks, 178 from carbonate rocks, and 19 from serpentine were found that were suited to the study here reported. Distribution of the samples throughout the United States is far from uniform, however. Moreover, identification of the rock making up the aquifers from which most of the samples analyzed were obtained is necessarily inexact.

A graphic device, consisting of five concentric logarithmic cycles and any convenient number of radii, permits plotting large numbers of chemical constituents having a wide range of concentrations on a single diagram. However, the flexibility and convenience of this diagram is offset by various disadvantages in comparison with earlier geochemical graphic methods and the universally satisfactory geochemical diagram has not yet been devised.

The circular graphs show recognizable differences between waters from igneous rocks and those from carbonate rocks but do not allow separation of waters from granite and waters from basalt. Basaltic-rock waters differ materially from granitic-rock waters in some regions. Comparison from region to region, however, shows that in some areas waters from basaltic rocks have characteristics apparently indistinguishable from the characteristics of granitic-rock waters in other areas.

The ratio, $\frac{\text{Ca} \times \text{HCO}_3}{\text{Na} \times \text{SiO}_2}$, all concentrations expressed in parts per million, separates carbonate-rock waters (ratio > 20) from waters derived from other rocks (ratio < 20) in 89 percent of more than 500 samples tested. Another ratio, $\frac{\text{Na} \times \text{Mg}}{\text{Ca}}$, also with constituents expressed in parts per million, provides separation of granitic-rock waters from basaltic-rock waters in apparently significant proportions of the samples tested. Using the latter relationship, a numerical ratio greater than 8 indicates basaltic waters in about 99 percent of the samples tested; a ratio greater than 4.5 suggests basaltic waters in about 90 percent of the tests; and a ratio of less than 1.5 apparently represents water from granitic rather than basaltic rock in 90 percent of the cases tested.

The results of the study imply: (1) that "monolithologic terranes" can seldom be identified with confidence, especially in reports of regional studies; (2) that graphic and arithmetic devices using the major constituents in waters, that is those characteristically reported, do not suffice to distinguish the rock-mineral assemblages with which the water has been in contact, save for carbonate-rock waters as a group; and (3) that different, and detailed, approaches must be employed in order to gain understanding of the geochemical interactions between water and its geologic environments.

INTRODUCTION

The relations of the chemical character of ground waters to their terranes of origin has been of interest for many years. Despite this fact, relatively few attempts have been made to describe and specify those relations. This paper reports on an attempt to find, in the reported chemical analyses of waters, unique and persistent characteristics that could be related directly to the monolithologic character of the aquifers. The term "monolithologic aquifer" is used in the sense of a body of rock of essentially homogeneous lithology and of sufficient extent to receive, store, and transmit water to springs or wells. Three types of terrane furnished most of the samples considered--granitic, basaltic, and carbonate rocks. In addition, a few waters derived from serpentine, and several groups of water samples from wells that penetrate sandstone aquifers are considered rather briefly.

In general, the results were not such as to encourage further work in this direction using published information. The routine reports of lithology of aquifers inadequately define the rock-mineral assemblages with which the water is in contact. The hydrology of the systems is characteristically incompletely known, hence the total history of water-mineral contact remains incompletely defined. Furthermore, extensive experimentation with graphic devices and with ratios among the major constituents--those reported in most water analyses--do not suffice to distinguish anything more than gross differences among waters from divergent rock terranes.

Previous work

Extensive review of the literature to 1960, suggests that relatively few attempts have been made to relate the chemical character of water obtained from surface or subsurface sources to the chemical character of rock terranes of origin. Where such chemical rock-water relationships have been discussed, they characteristically have been mentioned as incidental observations made during study of the hydrology of an area. Specific studies have occasionally related the chemical characteristics of a few water sources to a specific terrane, commonly of rather small areal extent. The following paragraphs offer a representative sampling of the literature, the items being discussed essentially in chronological order of their publication.

Arnold and Anderson (1908) described the occurrence of a white precipitate consisting largely of calcium and magnesium carbonate, having minor amounts of silica and iron oxide, which cements gravel along the lower course of White Creek in western Fresno County, Calif. White Creek derives its base flow from springs that emerge from serpentine in the upper drainage basin. The white deposits begin 2 miles downstream from the lower edge of the serpentine area and extend some 5 miles along the bed of the creek. The authors noted, but did not discuss, comparable deposits related to ultrabasic-rock terranes on Arroyo Mocho south of Tesla in Alameda County, Calif., and along two tributaries of the Trinity River in northern California.

Palmer (1911) recognized that interpretation of chemical analyses of water might be used to help determine the geologic environments of the waters and demonstrated the relationship with particular application in the case of carbonate-rock terrane. He also stated that a high percentage content of silica in waters is commonly related to terranes consisting of igneous rocks.

With respect to ground water in the San Jacinto and Temecula basins, Southern California, Waring (1919) remarked " * * * the high content of silica and carbonate, together with the large proportions of alkalies and very little calcium and magnesium shows plainly that the water is derived from granitic rocks." This observation proves to be somewhat at variance with relationships found as the result of a wider sampling which are discussed later in the present paper.

Clarke's (1924) tabulation of the composition of river and lake waters of the United States contains relatively little discussion of the geochemistry of the waters which he cited. He did note, however, (p. 48-49) that the rivers of the South Atlantic slope from Virginia to Georgia, were similar one to another, being low in calcium and high in alkalies and silica. He referred the situation to the fact that the rivers rise in the southern Appalachians where the terrane is dominated by sodic granite, stating that the silica and alkalies were derived from weathering of sodic feldspars.

An attempt was made by Bond (1946) to evaluate and categorize chemically the ground waters of the Union of South Africa, and in part to relate the chemical composition to the rocks from which the waters were derived. The attempt was handicapped by the fact that in many analyses sodium and potassium were determined by difference (Bond, 1946, p. 8). Among the observations made by Bond were the prevalence of high concentrations of chloride and of sulfate in waters derived from granite or gneiss in South Africa. He noted that high chloride concentrations correlate with high sulfate concentrations and implied (p. 166) that the correlation depends upon the influence of marine connate waters or of cyclic salts. He observed that shales, mudstones, and micaceous flagstones of the Cape system (Devonian and Lower Carboniferous) yield brackish waters, and stated as a general conclusion (p. 77) that argillaceous rocks tend to retain connate sea water and because of the low permeability of the rocks, to retain contained or absorbed salts. In consequence, he concluded that low concentrations of chloride and sulfate found in waters derived from argillaceous rocks would suggest that the rocks were deposited in fresh-water environment. He also concluded (p. 163) that it is generally impossible to identify the source rock of a water by its chemistry.

A discussion of ground-water resources of the Huntsville area, Alabama (LeMoreaux, Swindel, Jr., and Lanphere, 1950) showed that the water obtained from the Tusculum Limestone and Fort Payne Chert, both of Mississippian age, is consistently less highly mineralized than is water obtained from the Chattanooga shale of Devonian or Mississippian age.

LeGrand (1952, 1954, 1958) is one of the few who has published specifically on the relationship between water quality and rock terrane. He pointed out in 1952 "*** the mineral content of water from a short stream may reveal much information on the geology of its small drainage area," and stated further "*** where the circulation of water in different kinds of rock is equal, the chemical quality of the water reveals the general solubility of the source rock." With respect to the Statesville area in North Carolina, LeGrand (1954, p. 13) showed by means of tables and a brief discussion that in that area, at least, waters obtained from diorite or from hornblende gneiss contained characteristically three times as much dissolved solids as waters obtained from granite. The tabulation shows further that wells penetrating both granite and diorite yielded waters having mean concentrations intermediate between those of waters obtained from granite alone and waters obtained from diorite or hornblende gneiss alone. And in 1958 he characterized water from granitic rocks as being generally soft, slightly acid, and low in dissolved solids. He included in the group of granitic rocks granite, granite gneiss, mica schist, slate, and rhyolite flows and tuffs. He also found that water from dioritic rocks is hard, slightly alkaline, and high in dissolved solids. This group includes diorite, gabbro, hornblende gneiss, and andesite flows and tuffs. He concluded "*** lithologic determinations based on the chemical character of ground water are generally reliable in regions of similar climate and topography. Anomalies in dissolved mineral constituents not due to differences in rock type, climate or topography, may indicate either abnormal structural conditions, resulting in abnormal rates of circulation of the water, or presence of concentrated mineral deposits."

Two regional studies of note are those by Hembree and others (1952) and Colby and others (1956), dealing respectively with the Powder River basin in Wyoming and Montana and with the Wind River basin, Wyoming. Water from granitic terrane in the Powder River basin was characterized as having low dissolved-solids content in which silica makes up about 25 percent of the anhydrous residue, calcium nearly the same, carbonate 35 percent, and sodium, potassium, and magnesium together less than 5 percent. Water emerging from limestone in the same area had less than 10 percent silica, 20 percent calcium, and about 10 percent magnesium, 55 percent carbonate, and 1.2 percent sodium plus potassium. The study by Colby and others (1956) in the Wind River basin, differentiated the effects upon chemical quality of runoff of the relatively insoluble Precambrian rocks, of siliceous igneous breccias, and of consolidated and semiconsolidated sedimentary rocks of Mesozoic and Tertiary age. The differences observed are discussed in that report and are shown by graphic symbols on a map (pl. 8).

A brief discussion of the problem was offered by Keller (1957) who related the chemical quality of waters in nine rivers to their geologic environments and to the influences of man. The data used were taken largely from Clarke (1924), cited earlier in the present discussion. Keller, however, pointed out the common occurrence of high silica content in rivers draining igneous terranes under both temperate and tropical humid climatic conditions. He further commented on the chemical character of water draining limestone terrane, and the effects of mine drainage, paper-mill waste, and irrigation return flow upon selected streams. Keller suggested that for the general case (1) soluble ions are released during weathering about as would be predicted on the basis of hydrolysis and other reactions between water and minerals, (2) that the waters tend to reflect the rock materials and reactants and the energy of weathering (climate), and (3) the soluble constituents of weathering complement the solid residua to account for the composition of the unaltered parent rocks.

A paper by Anderson and Hawkes (1958) compared the chemical composition of stream waters and of rocks in their drainage basins in two localities in New Hampshire and one in Vermont, where the drainage basins had chemically homogeneous rock terranes. Principal attention was given to determining the orders of mobility of selected constituents. The determination was as follows: $Mg > Ca > Na > K > Si > Al = Fe$. A year earlier, Hawkes (1957) discussed the use of geochemical techniques in prospecting and the geochemical behavior of individual elements, especially metals having economic interest. A noteworthy bibliography is a part of his paper.

The behavior of silica in the sedimentary cycle was discussed by Siever (1957) who included the statement that with respect to other dissolved solids silica will be highest in the upper parts of streams that drain metamorphic or igneous-rock terranes where chemical weathering is at a maximum. In such streams silica alone amounts to an average of about 25 to 35 ppm.

The relationship of water quality to the geologic environment was discussed by Hem (1959, p. 201-216). The paper includes discussion of the types of water that should ideally emerge from various rock environments and the yields of individual constituents, especially silica, during chemical weathering of some of the major rock-forming minerals. The discussion is largely general in nature, treating igneous, sedimentary, and metamorphic rocks as groups. Individual rock types are treated only by a few examples. Variations in chemical quality of water from a single rock type, but occurring in varied environments, are to be expected as climatic influences affect rates and types of weathering of the rock-forming minerals, according to Hem. Waters from igneous rocks show a direct relation between silica and sodium contents--high concentrations of silica being characteristically common in waters having high sodium percentages and low silica concentrations being found in waters associated with rocks having larger proportions of ferromagnesian minerals. In waters characterized by high sodium and alkalinity, an upper limiting value for silica can be roughly calculated by assuming that four molecules of SiO_2 are produced for each two Na^+ ions. Waters from dolomite should contain approximately equivalent amounts of calcium and magnesium, and by implication waters from limestone should contain an appreciably greater amount of calcium than of magnesium considered in terms of equivalents per million.

The foregoing citations suffice to show that difficulty has been experienced in relating water quality to rock terranes of origin, that in local areas success has been obtained, that water from carbonate-rock terrane is generally distinctive in chemical character, and that the character of water obtained from granitic rocks in South Africa, for example, diverges markedly from the general character of waters from granitic rocks observed elsewhere in the world.

Later sections of the present paper will show that in large part the generalities just stated appear to prevail. A few persistent rock-water relations apparently occur, but in many places waters in contact with rocks of quite divergent chemical composition nevertheless bear strong resemblances, and in fact are often indistinguishable one from another by means of major constituents.

Monolithologic terranes

As defined earlier, a monolithologic terrane, for the purposes of the present paper, consists of an area underlain by rock having generally homogeneous composition, and sufficiently large to receive, store, transmit, and discharge significant amounts of water that has been in contact exclusively, or largely, with only one rock type during the time of its existence as ground water. Terranes having such characteristics are at best uncommon. Speaking of the Mesozoic granitic rocks of central California, Hamilton (1956) says that the Sierra Nevada batholith consists of "hundreds of separate plutons; adjacent plutons may be of widely different composition, but the average composition changes irregularly eastward from quartz diorite to quartz monzonite."

The Snake River Plain of Idaho is underlain by many hundreds of feet of basalt and, therefore, should be representative of a monolithologic basaltic terrane. In point of fact, however, there is interlayered with the basalt at many localities and at many different horizons, sedimentary material both fluvial and lacustrine in origin. Furthermore, some of the recharge occurs by streamflow onto the northern part of the Snake River Plain. This streamflow originates in mountainous areas underlain by rocks of varied lithologic types. Ground water emerging from the Snake River Plain either as spring discharge or by pumping from wells, is therefore water that has been in contact not only with basaltic rocks, themselves variable in composition, but also during the course of its travel, with sedimentary materials having diverse chemical characteristics. Finally, since the inception of extensive irrigation on the Snake River Plain, much of the water now discharged by springs in the canyon of the Snake River consists of water of various surface origins applied in excess to the irrigated lands. Such water undergoes increase in mineral content attributable to evaporation and transpiration and to increments of chemical constituents derived from the soil during its passage downward, and from fertilizers, insecticides, and other contaminants added by man.

Any geologist who has measured stratigraphic sections or otherwise made detailed studies of carbonate rocks, is well and intimately aware of the variations that occur horizontally and vertically in rock types commonly found in carbonate-rock terranes, and with the abundant interbeds of shale and other rock types that occur in association with limestone and dolomite.

It is true, also, that identification of rocks composing aquifers from which water samples are taken, is frequently made on the basis of cursory inspection only and the assignment of a rock name is frequently unsupported by microscopic examination and seldom supported by chemical analysis of the rock reported.

With these considerations in mind, it is apparent that the term "monolithologic terrane" expresses at best a generalization. It appeared desirable, nevertheless, to make a broad study attempting to relate chemical quality of waters to major rock types. The natural starting point, therefore, became one of defining the rock types to be examined. Three major monolithologic types were selected for study, namely, the granitic, the basaltic, and the carbonate rocks.

It was necessary, furthermore, to assume that lengthy contact of water with the minerals composing an aquifer would impose the chemical characteristics of a "monolithologic terrane" upon the water, even though the water earlier might have been in contact with rocks of a composition different from that of the monolithologic terrane being examined.

Analyses of igneous rocks were taken from the compilation made by Washington (1917) and were selected from the groups that he classified as superior analyses. In addition, the groups were chosen so as to span the ranges of chemical composition represented by granitic and basaltic rocks. Thus, 50 samples reported as granite were selected from the group of superior analyses reported by Washington, using every fifth analysis starting from the salic end of the range, and 50 analyses reported as "quartz monzonite" or as "granodiorite" were selected starting from the felsic end of the tables. In the same fashion, 50 samples reported as "andesite" were selected from the salic end of the tables and 50 reported as "basalt" were selected from the felsic end of the tables. The results show significant differences in chemical composition in spite of broad overlap that occurs in many individual constituents. Considering the groups individually, silica is more abundant in the granitic rocks and on the average potassium likewise makes up a somewhat greater proportion of the total rock in the granitic group. On the other hand, both ferric and ferrous iron are more abundant in the basaltic group of rocks as are magnesium, calcium, and titanium. The other constituents reported in the tables show little variation between the two groups.

For the purposes of the present study it was assumed that the differences in rock composition observed on the basis of the compilation, adequately define the chemical differences to be expected between monolithologic terranes of the granitic and the basaltic types.

Sources of analytical data

The chemical analyses of water from monolithologic terranes are from many sources. More than half of the analyses selected to illustrate basaltic and granitic waters were made in the project laboratory at Menlo Park, Calif., and are unpublished. Other unpublished data were also used in calculating ratios and related studies reported later in this text. Many analyses, however, including all those of carbonate-rock waters, were taken from published sources. The references used in these compilations are reported below, grouped according to the types of terrane represented, where appropriate.

Water from basaltic rocks

Feth, J. H., 1954, Preliminary report of investigations of springs in the Mogollon Rim region, Arizona, with sections on base flow of streams by N. D. White, and on quality of water by J. D. Hen: U.S. Geol. Survey open-file report (Tucson, Ariz.).

Hall, G. M., 1934, Ground water in southeastern Pennsylvania, with analyses by M. D. Foster, and C. S. Howard: Pennsylvania Geol. Survey 4th ser. Bull. W. 2, 255 p.

Hart, D. H., and Newcomb, R. C., 1956, Preliminary report on the ground-water resources of the Tualatin area, Oregon: U.S. Geol. Survey open-file report (Portland, Oreg.) 165 p.

Hogenson, G. M., 1956, Geology and ground-water resources of the Umatilla basin, Oregon: U.S. Geol. Survey open-file report (Portland, Oreg.), 215 p.

Littleton, R. T., and Audsley, G. L., 1957, Ground-water geology of the Alpine area, Brewster, Jeff Davis, and Presidio Counties, Texas: Texas Board of Water Engineers Bull. 5712, 87 p.

Lohr, E. W., 1957, Chemical character of public water supplies of the larger cities of Alaska, Hawaii, and Puerto Rico, 1954: U.S. Geol. Survey Water-Supply Paper 1460-A, p. 1-39.

Piper, A. M., 1932, Geology and ground-water resources of The Dalles region, Oregon: U.S. Geol. Survey Water-Supply Paper 659-B, p. 107-189.

Stearns, H. T., Crandall, Lynn, and Steward, W. G., 1939, Geology and ground-water resources of the Snake River plain in southeastern Idaho: U.S. Geol. Survey Water-Supply Paper 774, 268 p.

Water from granitic rocks

Billingsley, G. A., Fish, R. E., and Schipf, R. F., 1957, Water resources of the Neuse River basin, North Carolina: U.S. Geol. Survey Water-Supply Paper 1414, 89 p.

Cederstrom, D. J., 1957, Geology and ground-water resources of the York-James peninsula, Virginia: U.S. Geol. Survey Water-Supply Paper 1361, 237 p.

Clapp, F. G., 1910, Occurrence and composition of well waters in the granites of New England: U.S. Geol. Survey Water-Supply Paper 258-D, p. 40-47.

Fish, R. E., LeGrand, H. E., and Billingsley, G. A., 1957, Water resources of the Yadkin-Pee Dee River basin, North Carolina: U.S. Geol. Survey Water-Supply Paper 1415, 115 p.

Hem, J. D., 1957, written communication - waters from granite of Idaho batholith.

Water from carbonate rocks

Beckman, H. C., and Hinchey, N. S., 1944, The large springs of Missouri: Missouri Geol. Survey Repts, 2d ser., no. 29, 141 p.

Brown, R. F., 1954, Public and industrial water supplies of the Mississippian Plateau region, Kentucky: U.S. Geol. Survey Circ. 341, 38 p.

Capps, S. R., 1910, The underground waters of north-central Indiana with a chapter on the chemical character of the waters by R. B. Dole: U.S. Geol. Survey Water-Supply Paper 254, 279 p.

Ferguson, G. E., Lingham, C. W., Love, S. K., and Vernon, R. O., 1947, Springs of Florida: Florida Geol. Survey Bull. 31, 196 p.

Holt, C. L. R., Jr., 1956, Geology and ground-water resources of Medina County, Texas: Texas Board of Water Engineers Bull. 5601, 278 p.

Johnston, W. D., Jr., 1933, Ground water in the Paleozoic rocks of northern Alabama: Alabama Geol. Survey Spec. Rept. 16, pt. 1, 414 p.

Piper, A. M., 1933, Ground water in southwestern Pennsylvania: Pennsylvania Geol. Survey 4th ser. Bull. W. 1, 406 p.

Robinson, W. H., Ivey, J. B., and Billingsley, G. A., 1953, Water supply of the Birmingham area, Alabama: U.S. Geol. Survey Circ. 254, vi, 53 p.

Warren, M. A., 1944, Artesian water in southeastern Georgia with special reference to the coastal area: Georgia Geol. Survey Bull. 49, 140 p.

Water from serpentine

Hall, G. M., 1934, Ground water in southeastern Pennsylvania, with analyses by H. D. Foster, and C. S. Howard: Pennsylvania Geol. Survey 4th ser. Bull. W. 2, 255 p.

Mack, Seymour, 1958, Geology and ground-water features of Scott Valley, Siskiyou County, Calif.: U.S. Geol. Survey Water-Supply Paper 1462, 95 p.

Waring, G. A., 1915, Springs of California: U.S. Geol. Survey Water-Supply Paper 338, 410 p.

Runoff

Connor, J. G., Mitchell, C. G., and others, 1958, A compilation of chemical quality data for ground and surface waters in Utah: Utah State Engineers Tech. Pub. 10, 276 p.

U.S. Geological Survey, 1959, Quality of Surface Waters of the United States 1955, pts. 9-14, U.S. Geol. Survey Water-Supply Paper 1403, 437 p.

Selection of analyses. Mention has been made earlier, in the section on the rocks, of the fact that many analyses are reported as representing water obtained from a specific rock type despite the fact that identification of the rock in field and laboratory has been based on insufficient study of the rock itself. This element of uncertainty remains inescapable in any compilation of water analyses made from the literature. With respect to water from wells, the field man taking the water sample is further handicapped in most places by the fact that he is identifying the rock of the aquifer on the basis of reports, sometimes written but more often oral, of the owner or of the driller of the well. Especially in the case of older wells where time has erased the freshness of man's memory, identification of rocks based on such reports is frequently and necessarily uncertain. The compiler of water-quality data is therefore seldom very sure of the actual character of the rocks composing the aquifers from which the water samples were taken.

Furthermore, except in rare instances, the hydrology of the system from which the reported water samples were obtained is unknown or imperfectly known. The geochemical environment of the water is, therefore, also imperfectly defined and water reported as from "granite" may easily have been in contact for long periods of time, before or after recharge with various lithologic types.

In the present instance, the analyses were selected for compilation where the writer had reasonable grounds upon which to believe that a careful attempt had been made to identify, at least within broad classes, the rocks from which the water samples were taken. In each case the analysis selected was tied by specific reference in the published text or in the unpublished report, to one of the rock types of interest.

In addition, each analysis used was calculated from parts per million to equivalents per million and the sum of cation equivalents compared with the sum of anion equivalents to determine that a reasonable balance between the two existed in the reported analysis.

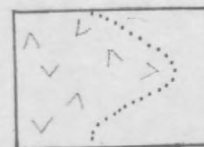
Uniform geographic distribution of the analyses selected for study has not been feasible. The data used, therefore, are heavily weighted as to geographic area by virtue of the abundance of analytical reports from some localities and the dearth of analytical reports from others. A majority of the waters from granitic rocks, for example, are obtained from reports from North Carolina. The State of Washington is inadequately represented in the tabulation of waters from basaltic rock because the writer found relatively few analyses reported from that State that were sufficiently complete and adequately identified as to source. The same situation is in large measure true with respect to the broad basalt-covered areas of northern California, except that personnel of the present project have collected some samples from that terrane.

Many older analyses in the literature, and not a few published in recent years as well, proved to be unsuited to use for present purposes either because they are restricted to only a few constituents or because the major constituents were reported with the exception of silica, and silica has been used as a determinant species in the work reported in this paper.

The number of analyses of water from carbonate rocks suitable for use in the present study is larger than the number from any other rock group dealt with. The geographic distribution of available information regarding waters from carbonate rocks is reasonably adequate for the southeastern States and for Texas, it is scanty for much of the middle west and is virtually nonexistent for the Western States.

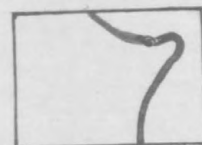
In summary, 75 analyses of water from basaltic rocks, 100 from granitic rocks, 178 from carbonate rocks, and 19 from serpentine were finally selected for study.

EXPLANATION



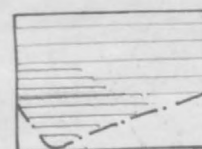
Water from granitic rocks.

Ⓒ Average of 100 analyses.



Water from basaltic rocks.

Ⓓ Average of 75 analyses.



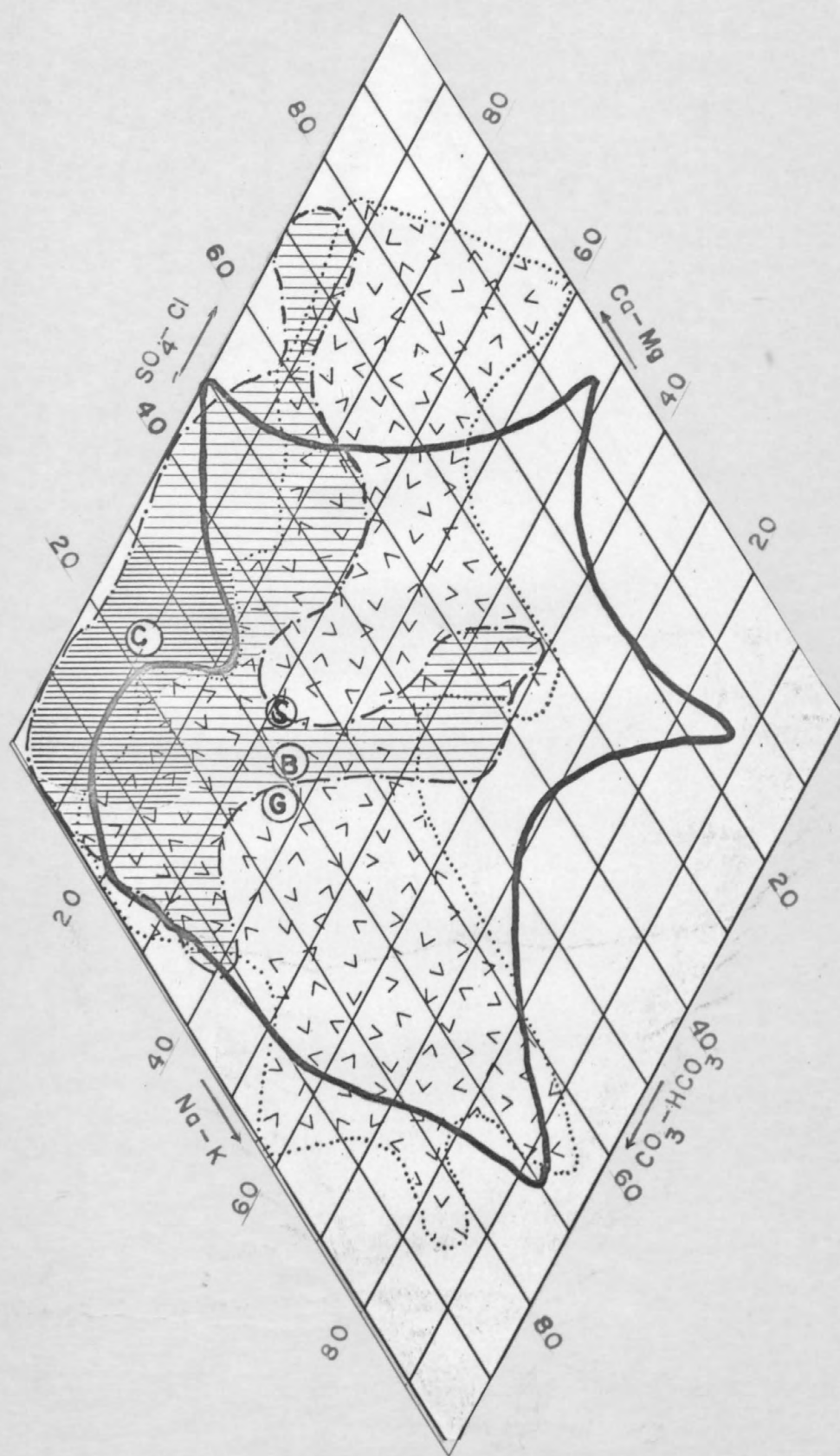
Water from carbonate rocks.

Ⓔ Average of 178 analyses.

Heavy-line area includes 60 percent of these.

Ⓕ

Average of 19 samples of
nonthermal water from
serpentine.



Percentage reacting values

Figure 1. Diagram showing the mean chemical character of water from basaltic, granitic, and carbonate rocks, and from serpentine.

Graphic representations of chemical character of water from monolithologic terranes

Dozens of schemes, graphic and otherwise, have been devised by various investigators in their attempts to organize and study water-quality data. Many of these have been discussed and illustrated by Hem (1959, p. 149-201). Among the more useful is the device by Piper (1944) which was used in preparation of figure 1.

Figure 1. Diagram showing the mean chemical character of water from basaltic, granitic, and from carbonate rocks, and from serpentine.

The diagram was prepared by calculating the mean composition of the monolithologic-terrane waters selected for study in this report, and shows that in overall composition the average water from each of the four rock types is calcium magnesium bicarbonate in character. The limestone water, as might be expected, is notably high in calcium, that from serpentine is notably high in magnesium, but water from granitic and basaltic rocks is not distinguished by large differences among the cations. Water from all four rock types differs little in anion content. The diagram also shows that water from basaltic terrane and granitic terrane cannot be distinguished by use of a diagram, and that there is appreciable overlap of both upon the carbonate-rock field. The water from carbonate rocks, however, shows tighter grouping than the others. In fact, about 60 percent of the carbonate-rock waters studied plot on the diagram within a small area on the diagram. Because the overlap was equally apparent during the writer's attempts to employ other graphic devices, he was brought finally to adopt a modification of logarithmic graphic schemes upon which to represent the chemical characteristics of waters.

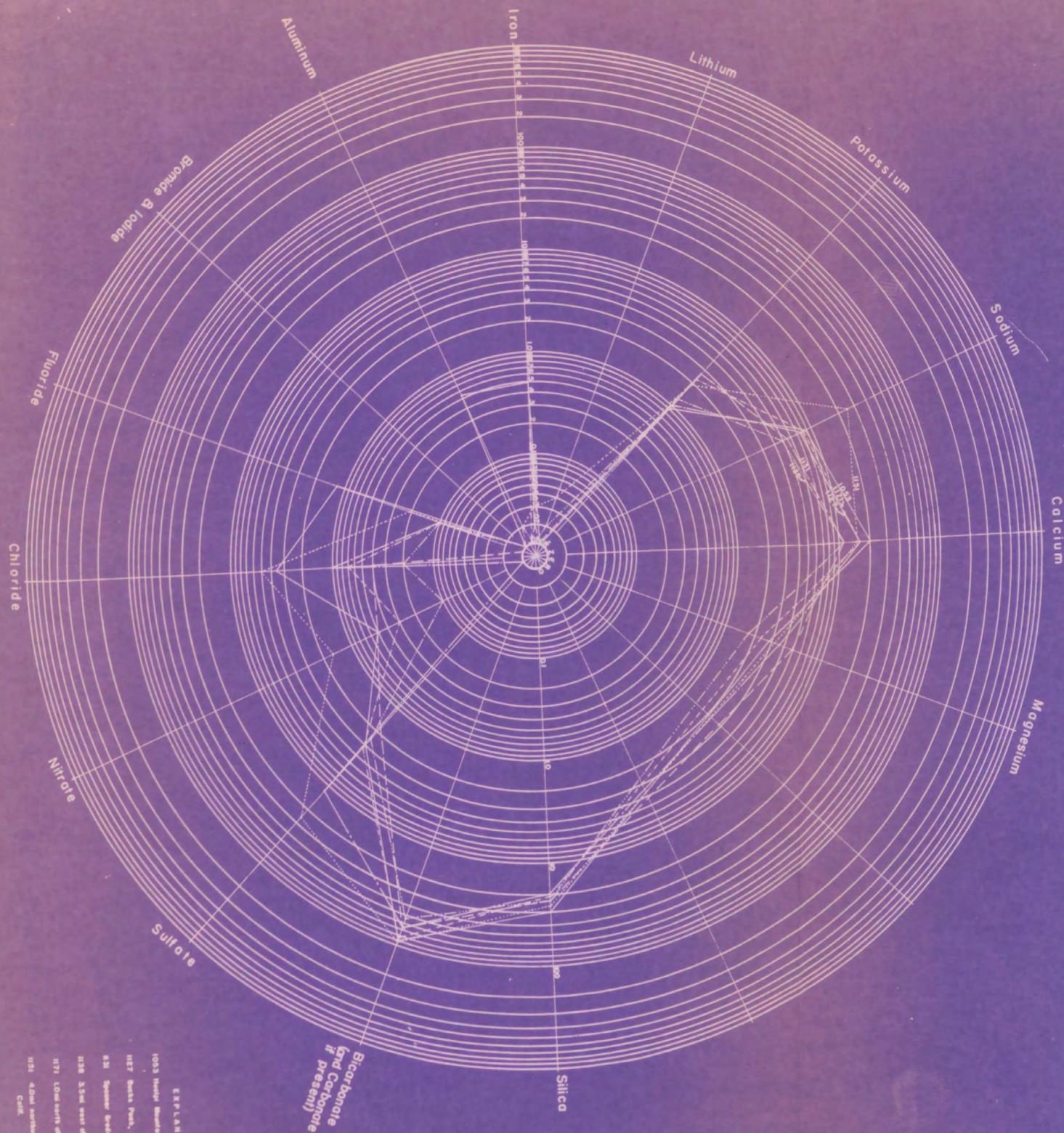


Figure 2. Diagram showing the chemical character of representative nonthermal spring water from granitic rocks.

The charts consist of five concentric logarithmic cycles upon which have been drawn equally spaced radii, each radius representing one constituent, the concentration of which is to be illustrated. The use of the logarithmic scale permits the direct plotting of very small amounts of individual substances (to 0.01 ppm) and quite large (1,000 ppm) concentrations on a single diagram. Inasmuch as the number ^{of} radii can be adapted to individual needs, the graph permits plotting as many individual constituents as may be desired. From these points of view, the diagram is flexible. Because the parameter selected for plotting is parts per million, the unit normally used in reporting modern water analyses, the graph is also convenient to use. It does not, however, permit comparison of waters with respect to mixing as does the trilinear diagram, and as usual with graphic devices it is suitable for some purposes of comparison but totally unsuited to others. The universal graphic device with which to study water analyses has not been devised, and probably never will be.

Water from granitic terrane

Figure 2 shows the chemical character of 6 spring waters emerging from granitic rock in the Western States. These waters have been selected

Figure 2. Diagram showing chemical character of representative nonthermal spring water from granitic rocks.

for illustration because they were all collected by project personnel under controlled conditions and analyzed in considerable detail in the project laboratory. They are considered representative of spring waters emerging from granitic terrane in the Western States, in areas where

there is little if any influence from the activities of man, where precipitation is moderately abundant, and where the water has been in contact only with granitic rock during its time of occurrence as ground water. With the exception of Nos. 1053 and 1127, the rock represented is part of the Sierra Batholith.

The outstanding features shown on figure 2 are the relatively gentle slope of lines connecting sodium and calcium values of individual analyses, the nearly straight line from calcium across magnesium to silica, and the sharp downward inflection from the silica value toward bicarbonate. This configuration is considered representative of waters from granitic rocks in the geographic area of concern and of waters from basaltic terrane as well. The disorder in that part of the chart representing sulfate, chloride, and nitrate is characteristic of water from these sources.

It is obvious that the configuration, shown by the lines representing individual analyses, would vary if the arrangement of constituents on the circular diagram were different from that chosen. If a single arrangement of constituents is retained throughout a series of diagrams, however, comparisons may be made among them.

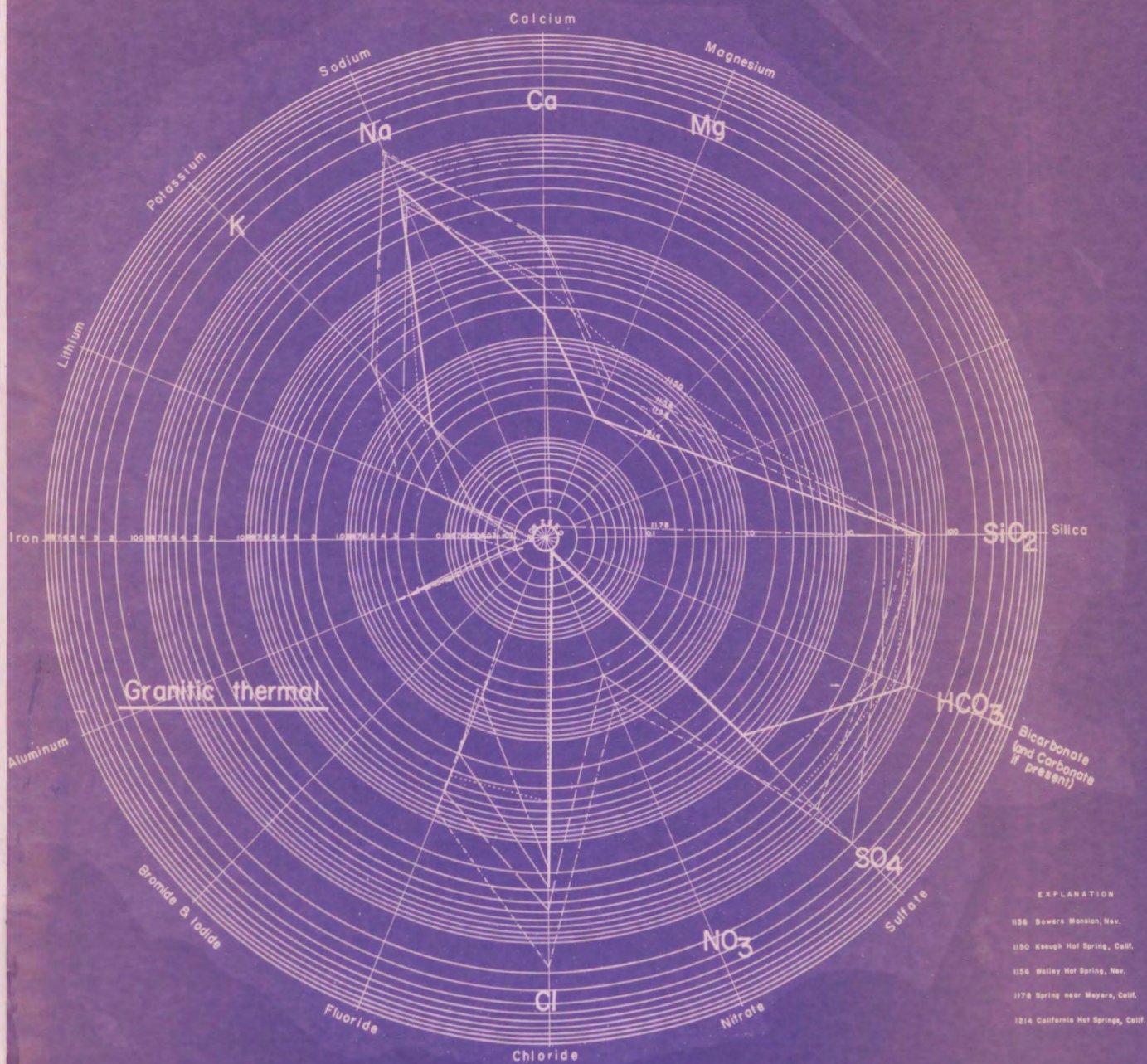
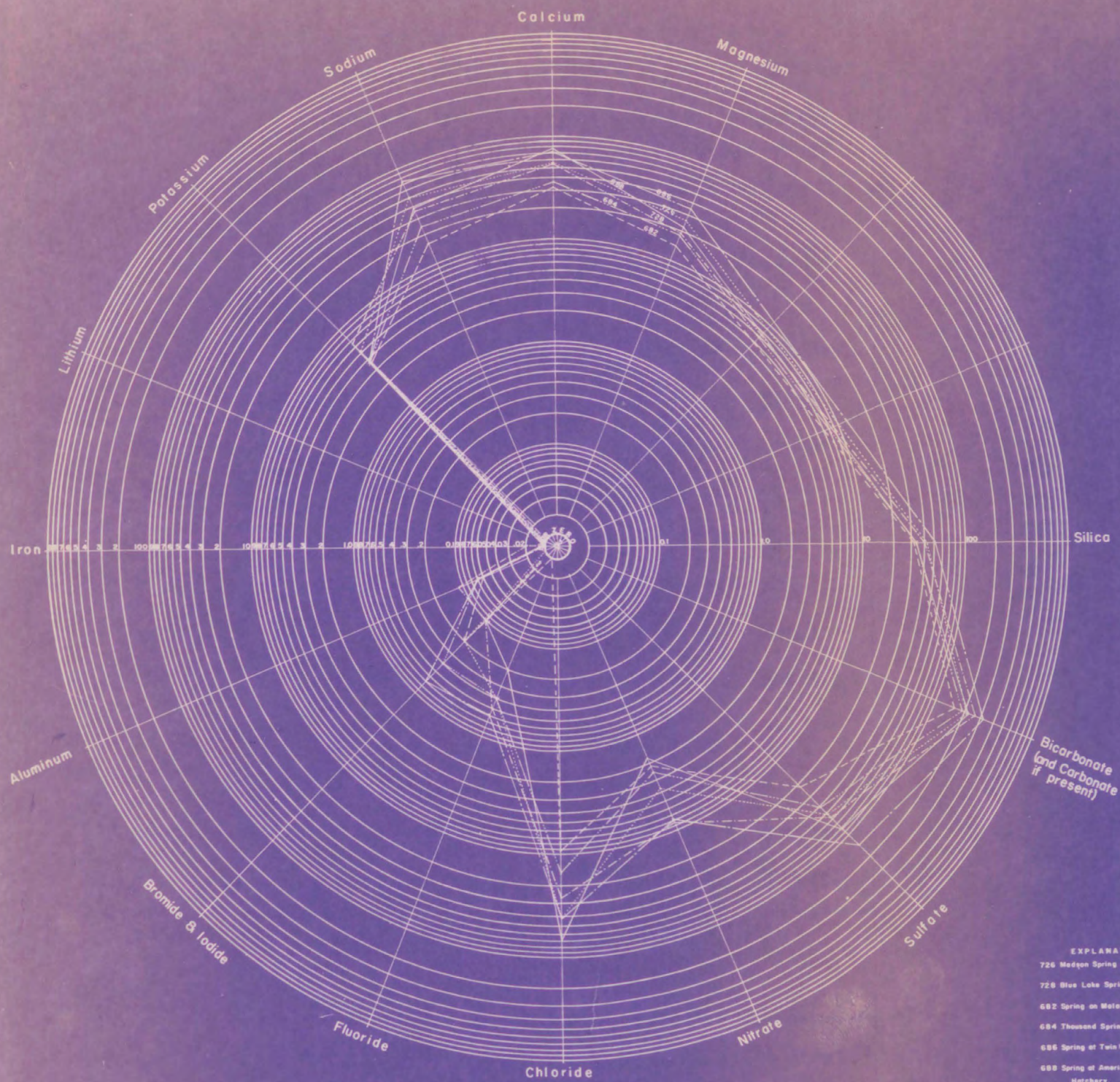


Fig.3. Diagram showing chemical character of thermal-spring water from granitic rocks.



EXPLANATION
 726 Madgeon Spring near Hagerman.
 728 Blue Lake Spring.
 682 Spring on Mated River.
 684 Thousand Springs.
 686 Spring at Twin Falls Hatchery.
 688 Spring at American Falls Hatchery.

Figure 4. Diagram showing chemical character of water from representative springs in basaltic rocks.

A small group of thermal waters issuing from granitic terrane is illustrated in figure 3. Without exception in the samples available

Figure 3. Diagram showing chemical character of thermal-spring water from granitic rocks.

from Nevada or California, the thermal waters from granite and related rocks are notably high in their content of sodium and notably low in content of magnesium, reaching the point of disappearance in sample 1178. The group of thermal waters is noteworthy also because of their relatively high contents of lithium and of sulfate or chloride, or both, and because the pH of the waters is uniformly in excess of 8.0. The high sulfate and chloride values observed are reminiscent of waters from granitic rocks in the Union of South Africa reported by Bond (1946). Many of the South African waters are thermal.

Water# from basaltic terrane

Several of the waters shown in figure 4 are among the more clear-cut cases of monolithologic-terrane water that are known to the writer,

Figure 4. Diagram showing chemical character of water from representative springs in basaltic rocks.

and all are thought to be representative of water emerging from basaltic rocks in areas having 20 or more inches of rainfall per year. The principal differences between basaltic water represented in figure 4 and the nonthermal granitic water shown in figure 2 relate to the higher concentrations of sodium and of magnesium relative to calcium in the water from basaltic rocks. The same downward inflection of the lines in the area from silica to bicarbonate that was remarked upon with reference to the granitic waters appears in the diagrams representing waters from basaltic rocks. As will be shown later, this inflection is at variance with the patterns shown by plots of waters from carbonate rocks or from

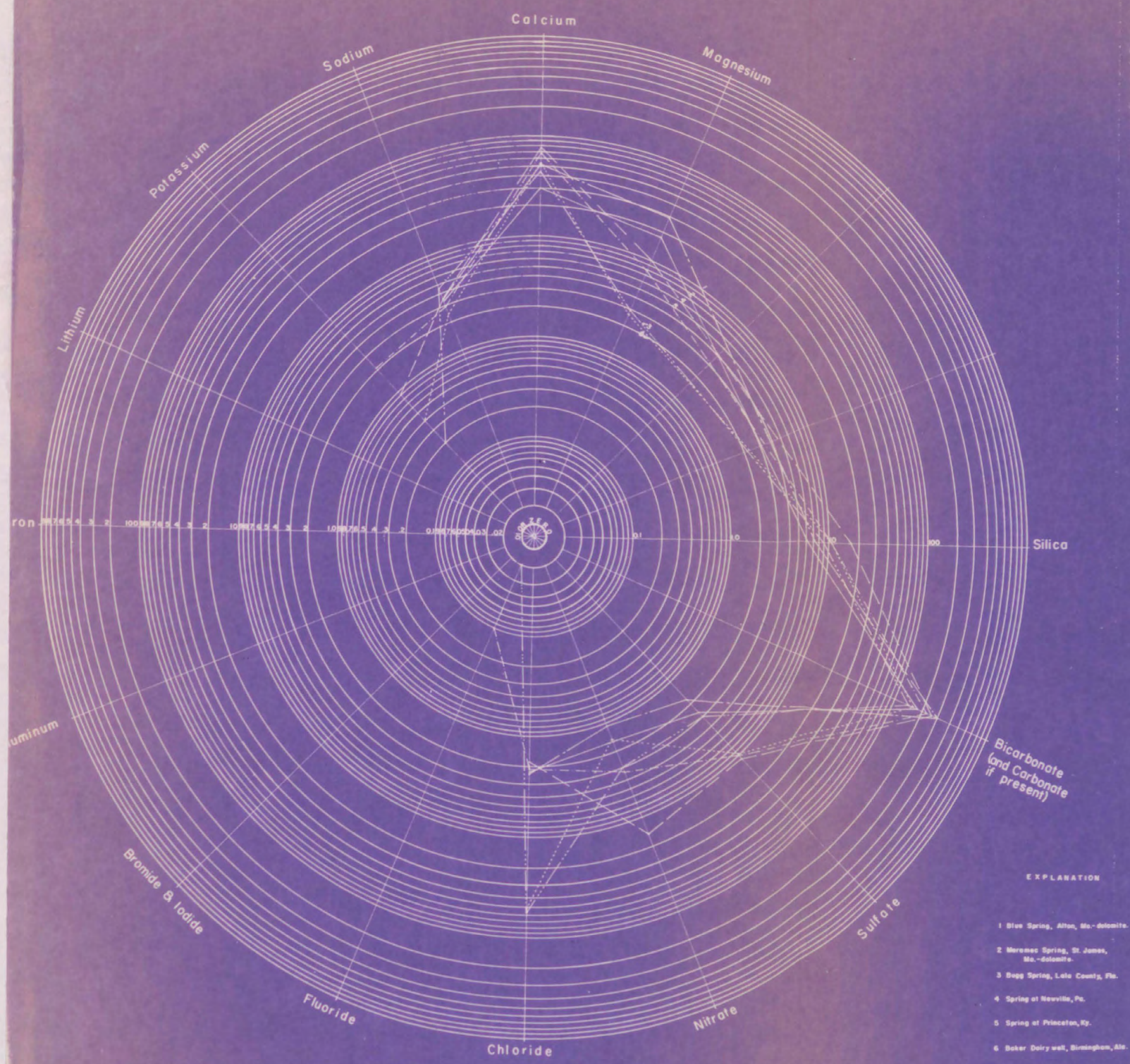


Figure 5. Diagram showing chemical character of water from carbonate rocks.

Waters from carbonate rocks

Analyses of water associated with carbonate-rock terranes are diagrammed on figure 5. The earmarks of these waters as they appear

Figure 5. Diagram showing chemical character of water from carbonate rocks.

on the circular diagram are functions of the high calcium value relative to sodium and the high content of bicarbonate relative to silica. In contrast to water from granitic or basaltic terrane, the line from the magnesium radius, through to the bicarbonate radius is, in the case of carbonate water, either gently convex downward or actually concave upward. The latter characteristic is shown on figure 5 by the dolomitic-rock springs Nos. 1 and 2. The resulting configuration, resembling a bird's head with a crest at calcium and the point of the beak at bicarbonate, is characteristic of waters from carbonate rocks. The diagram likewise shows grouping of the analyses represented into three types. Analyses 1 and 2 represent springs emerging from dolomite in Missouri and well display the high content of magnesium which is to be expected. Analyses 4 and 5, one from Pennsylvania and the other from Kentucky, are characteristic of water emerging from magnesian limestone, and carry a high content of calcium and an intermediate amount of magnesium in comparison with samples Nos. 3 and 6 which presumably relate to almost pure calcium carbonate limestone. In general, the behavior of water from carbonate-rock terrane is that which might be expected in view of the chemical composition of the host rocks and in view of the relatively high solubility shown by carbonate rock in the presence of water containing dissolved carbon dioxide.

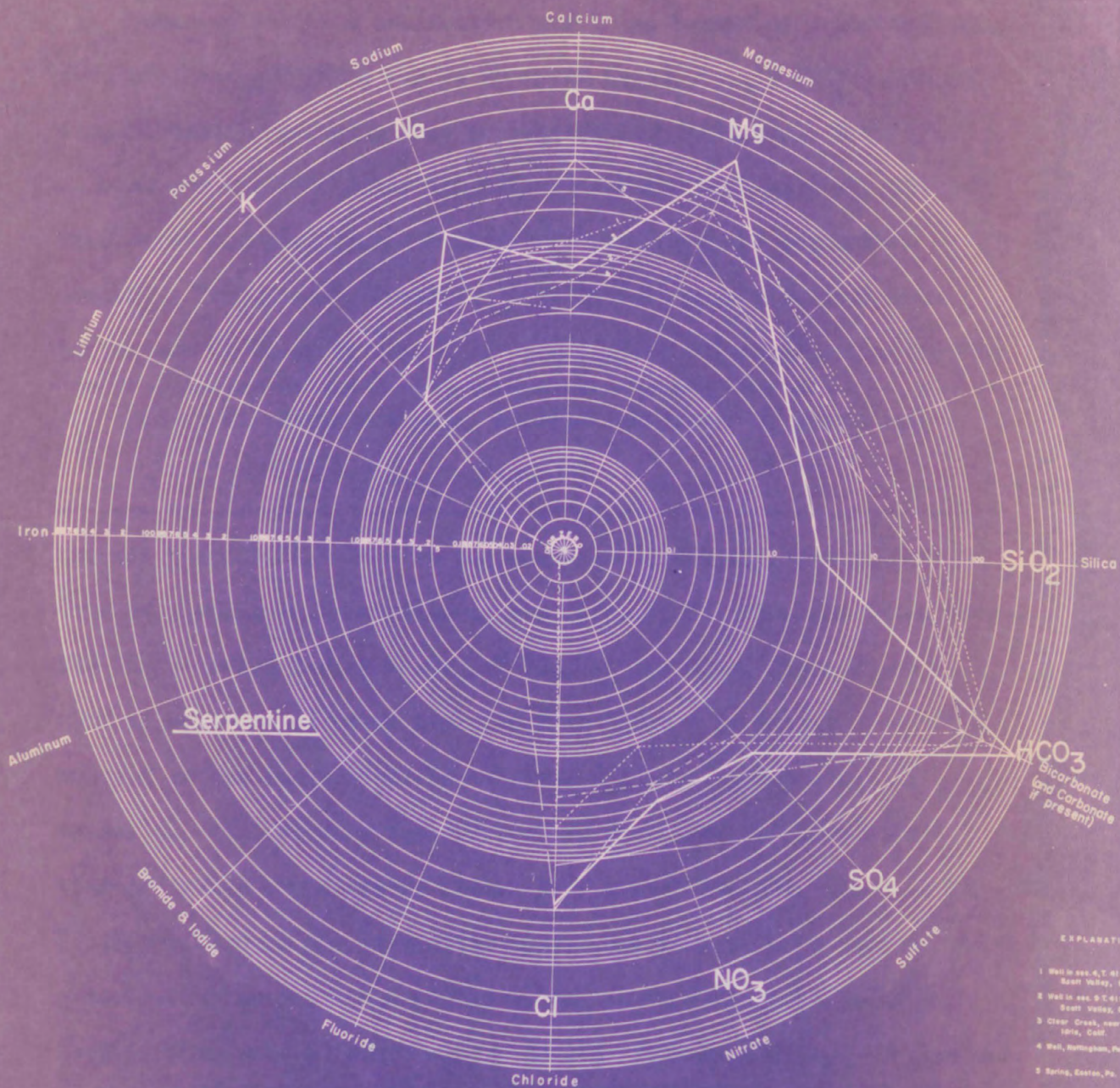


Figure 6. Diagram showing chemical character of nonthermal water from serpentin

Waters from serpentine

Relatively little information was found regarding water emerging from serpentine. Among the 19 analyses found, nearly half are from thermal springs emerging from serpentine in California. These thermal springs are highly mineralized for the most part and are not considered representative of water emerging from the serpentine terrane. The general character of nonthermal waters derived from serpentine is shown by figure 6. The diagram illustrates samples from

Figure 6. Diagram showing chemical character of nonthermal water from serpentine.

two wells in Scott Valley in far northern California, two sources from serpentine in Pennsylvania, and (fig. 6, No. 3) Clear Creek near New Idria in San Benito County, Calif. At low flow, Clear Creek is made up entirely of water emerging from springs in serpentine. With respect to the low content of calcium, the very high content of magnesium, and the very high content of carbonate and bicarbonate that generally characterize waters from serpentine, the water of Clear Creek conforms to the serpentine type. However, perhaps because it is a surface water and not a ground water, it is much lower in silica content than are the other waters derived from serpentine. The normal abundance of magnesium and of silica in these waters is presumably to be related directly to the chemical composition of the rock itself, and the relatively high content of iron shown by samples 4 and 5 would likewise appear to be consistent with this hypothesis. The fact that Clear Creek has a low iron content is expected because the iron content of natural waters diminishes very rapidly upon their emergence from the ground. Iron was not determined in the waters from the two wells in northern California.

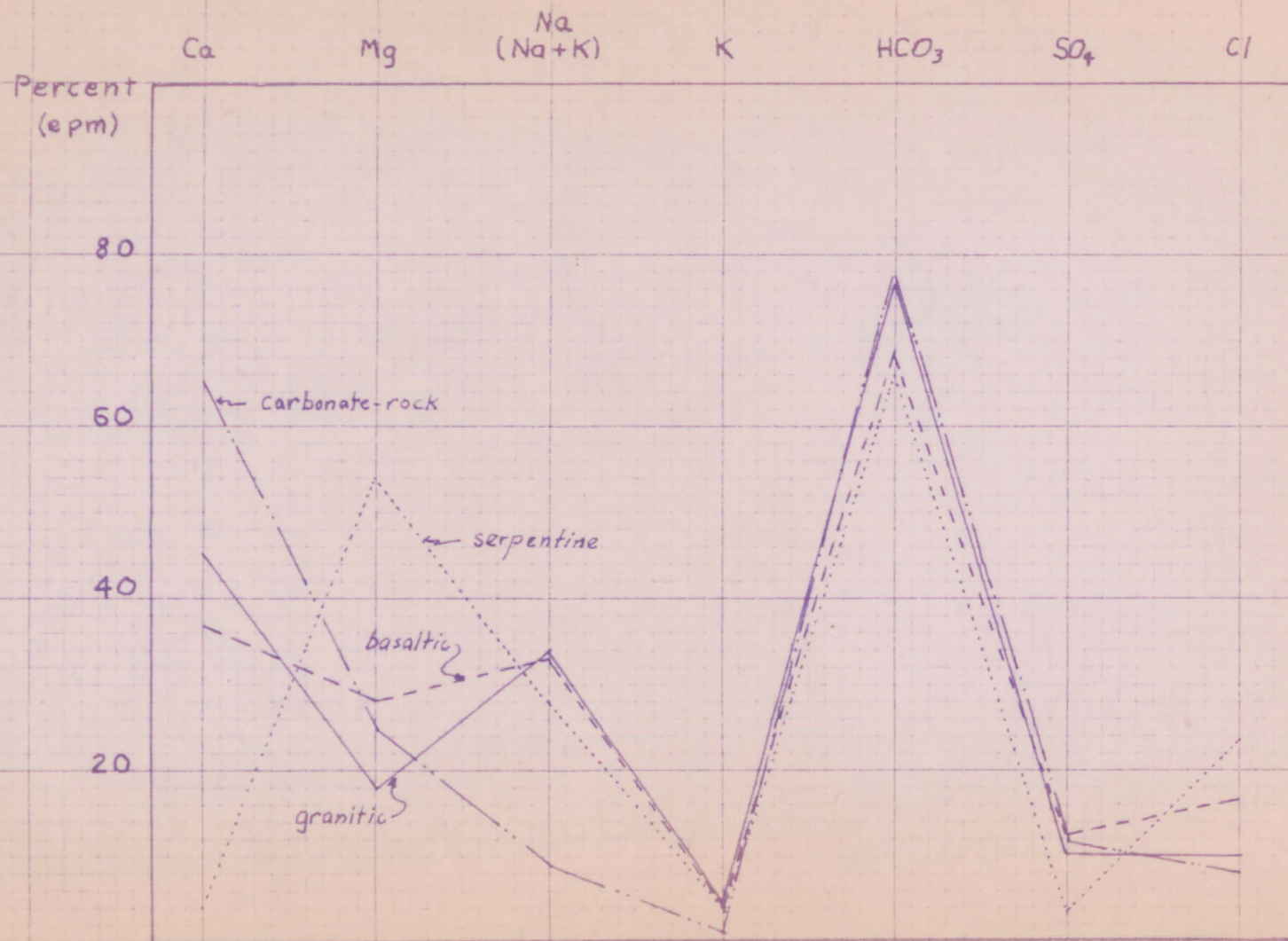


Figure 7. Comparison of mean percentages of major ions in water from granitic, basaltic, and carbonate rocks, and from serpentine.

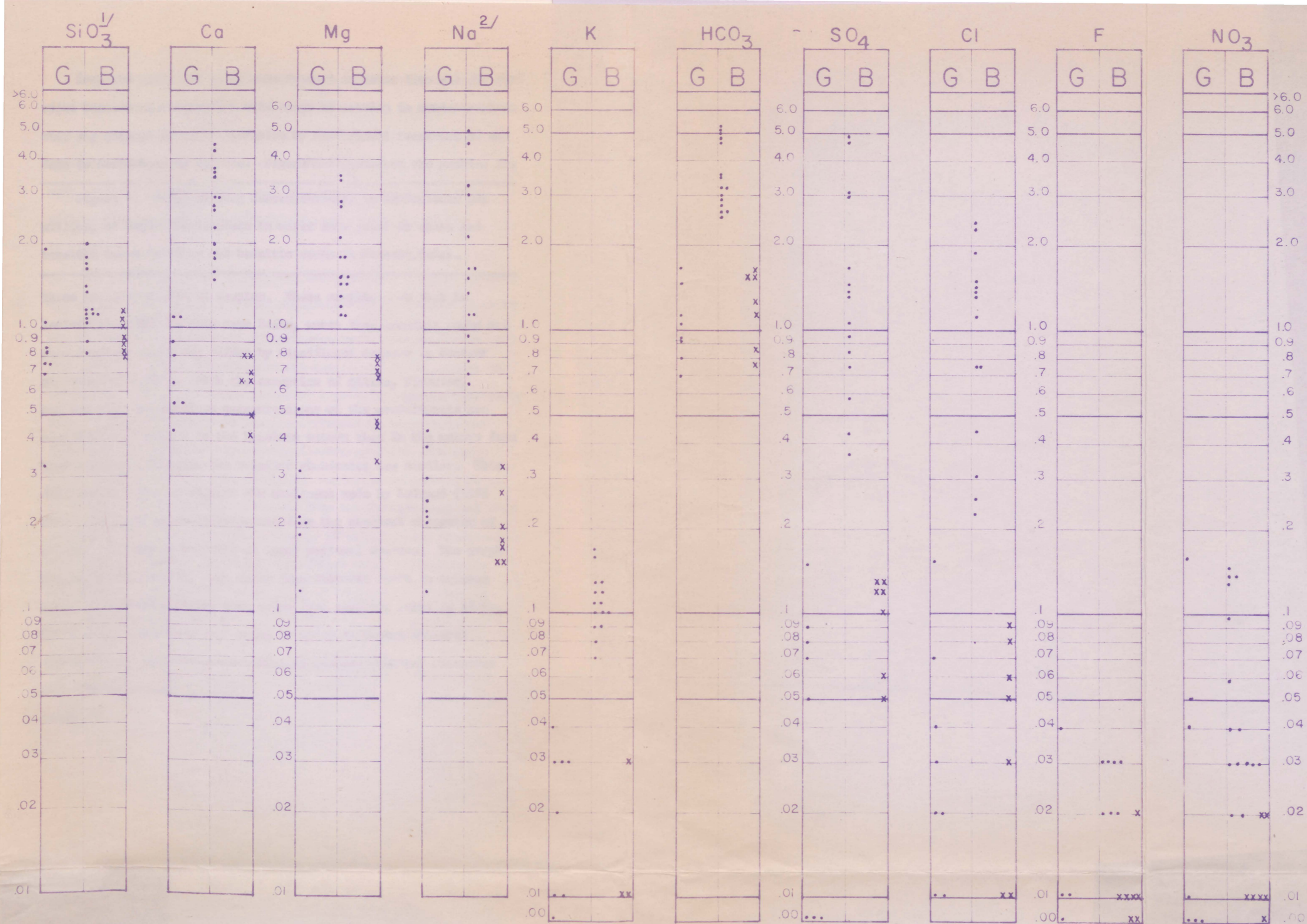
Ratio studies

Review of the circular diagrams makes it clear that relationships among the major constituents dissolved in ground water serve reasonably well to distinguish carbonate-rock waters. They do not, however, suffice diagrammatically to separate water derived from basaltic rocks from those originating in granitic rock. This is true even in the most nearly characteristic waters selected for illustration in this paper. It is even more apparent when dozens of analyses are charted on the circular diagrams. The trilinear diagram (fig. 1) further shows that the fields of water from granitic, basaltic, and carbonate rocks overlap widely. Additional points of approach, therefore, were examined in an attempt to find a device that would satisfactorily separate basaltic-rock and granitic-rock water analyses.

As a first attempt, the major constituents in the waters selected for study were reduced to percentages and the resulting mean percentages were plotted on a diagram (fig. 7). The lines representing waters

Figure 7. Comparison of mean percentages of major ions in waters from granitic, basaltic, and carbonate rocks, and from serpentine.

from granitic rocks and basaltic rocks travel nearly parallel courses across the percentage diagram, the major point of distinction being in the higher magnesium and lower calcium percentages found in water from basaltic rocks.



Feth 1960

1/ Silica calculated as equivalent ions, if it were dissociated.
2/ Includes potassium in some samples.

Columns "G" refer to water from granite; "B" to water from basalt.
• - Water from Idaho; x - Water from Arizona.

Figure 8. Graph showing concentrations, in equivalents per million, of major constituents in water from granitic rocks and basaltic rocks in Idaho, and basaltic rocks in Arizona.

Both the major and minor constituents in water from all the rock types considered show such a wide range of overlap in concentrations that any attempt to make separation by statistical treatment of the data is foredoomed to failure. Figure 8 illustrates the problem for

Figure 8. Graph showing concentrations, in equivalents per million, of major constituents in water from granitic rocks and basaltic rocks in Idaho and basaltic rocks in Arizona. ~~(fig. 8)~~.

three selected groups of samples. These samples show that in individual areas, in this case Idaho, water from granitic rocks and from basaltic rocks may differ by significant degrees in content of dissolved solids. With the exception of silica, fluoride, and nitrate, the absolute concentrations of the constituents are significantly greater in the basaltic waters than in the waters from granitic rocks although the relative abundances are similar. This distinction tends to confirm the statement made by LeGrand (1958) that lithologic determinations based on the chemical character of ground water may be reliable in local regional studies. The graph (fig. 8) shows, however, that water from basaltic rocks in Arizona would be indistinguishable from water from granitic rocks in Idaho. It appears, therefore, that rocks of quite different chemical character may yield waters of strongly similar chemical character when the rocks weather under different conditions of climate and topography.

A large number of ratios based on the major constituents dissolved in the water were studied in an attempt to find relationships that would characterize water from a monolithologic terrane. Each possible pairing of constituents was tried and many ratios in which constituents were combined were also tried without discovery of a relationship unique to any one of the terranes.

Two ratios did emerge, however, that approach the goal sought. One ratio, $\frac{\text{Ca} \times \text{HCO}_3}{\text{Na} \times \text{SiO}_2}$, all concentrations being expressed in parts per million, separates water of carbonate-rock terranes (ratio >20) from water of other rock environments (ratio <20) in 89 percent of 558 samples tested. Elimination of 38 high-silica waters reportedly from the Ocala Limestone in Georgia increased to 94 percent the proportion to which the stated relationship applies. The study included water derived from the Dakota Sandstone in various parts of North and South Dakota, and water from the Carizzo Sand and from the Indio Formation, consisting largely of argillaceous sandstone and arenaceous shale, in Texas. The relationship appears to be reliable as an earmark of waters from carbonate-rock terrane in about 90 percent of the possible cases.

The effectiveness of this ratio may reflect the occurrence of two steady-state conditions in nature. In the carbonate-rock system, abundant calcium is readily available and sodium but sparsely represented. In the presence of water containing dissolved carbon dioxide, the rock-water system will trend toward equilibrium between the calcite of the rock and the carbonic acid of the water phase. In the other lithologic environments studied, sodium and silica are more abundant constituents of the mineral assemblages. The later stages of weathering of these minerals yield, in part, sodium aluminum-silicate clay minerals such as the kaolin group. These minerals, even if present mainly as films surrounding grains of little-altered minerals, are those in contact with water moving through the rock. The result is a tendency toward equilibrium between the water and the sodium-silicate phase.

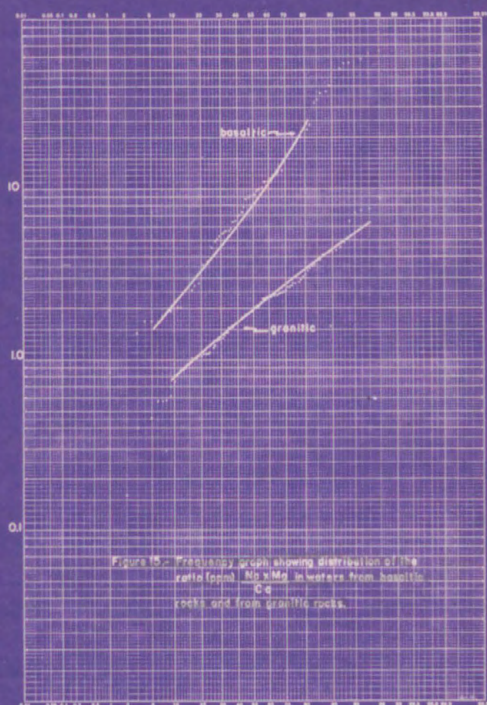


Figure 9. Frequency graph showing distribution of the ratio $\frac{Na \times Mg}{Ca}$ in water from basaltic and granitic rocks.

An additional ratio has some use in differentiating waters from various igneous-rock terranes. This is the ratio $\frac{\text{Na} + \text{Mg}}{\text{Ca}}$, all concentrations expressed in parts per million, and is illustrated by figure 9. The total group of analyses, 100 waters from granitic

Figure 9. Frequency graph showing distribution of the ratio $\frac{\text{Na} + \text{Mg}}{\text{Ca}}$ in water from basaltic and granitic rocks.

terrane and 75 from basaltic, was used in preparing the graph (fig. 9), disregarding influences of climate and topography in the various areas for which information was available. The distributions obtained suggest that where the ratio is numerically greater than 8, there is about 1 percent probability that the water is from granitic rocks, and 99 percent probability that it is from basaltic. Where the ratio is 4.5, there is a 10 percent probability that the water is from granitic, not basaltic, rock. And where the ratio is 1.5 or smaller, the likelihood is more than 95 percent that the water is from granitic rather than basaltic rock. The ratio has not been tested for broad application with respect to waters from other lithologic types.

In summary, it appears possible to recognize water derived from carbonate rocks in about 90 percent of all examples tested, using the ratio $\frac{Ca \times HCO_3}{Na \times SiO_2}$, and that the ratio $\frac{Na \times Mg}{Ca}$ may serve to distinguish waters from various igneous rock types when the application is restricted to environments in which the conditions of climate and topography are reasonably consistent. No other experimental relationships used in the present study seem to express characteristics that are in any way unique to water obtained from one of the selected monolithologic environments.

The results of an extended empirical study of water reported to be from monolithologic aquifers have thus been largely negative. Major difficulties encountered include inadequate definition of the chemical and mineralogical composition of the rocks that compose the aquifers. There is also a strong probability that, in many places, the climatic environment and products of weathering--not the original constituent minerals--exercise the larger control upon the chemical composition of water moving through the aquifers. Variations among major chemical constituents in the water apparently cannot be related to the mineralogical composition of the aquifers except in the most gross and obvious situations. And further efforts along these lines are not likely to produce useful results.

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also carried in stock in the following sizes

	HIGH		WIDE	THICKNESS		HIGH		WIDE	THICKNESS
	inches		inches	$\frac{1}{8}$ inch		inches		inches	$\frac{1}{8}$ inch
1523	9		7			1529	12	10	
1524	10		7			1530	12	9 $\frac{1}{8}$	
1525	9		6			1932	13	10	
1526	9 $\frac{1}{4}$		7 $\frac{1}{8}$			1933	14	11	
1527	10 $\frac{1}{2}$		7 $\frac{3}{8}$			1934	16	12	
1528	11		8						

Other sizes made to order.

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