Graphical Interpretation of Water-Quality Data

by Alexander Zaporozec[a]

ABSTRACT

Quality of water is determined by chemical analyses, the data from which are used for various purposes, such as classification, analysis, correlation, etc. For these purposes, the data need to be compiled and statistically evaluated. Graphical and numerical interpretation, a basic tool in hydrochemical studies, is one of the means used for summarizing and presenting water-quality data. There exist a considerable number of methods and procedures which can be applied. They are relatively simple and can be used without extensive knowledge of chemistry. Main techniques and methods are grouped, for the purpose of discussion, into four categories as to their possible use: classification methods, correlation methods, analytic methods, and synthetic and illustrative methods. The basic graphs and diagrams in each category are accompanied by examples.

INTRODUCTION

Knowledge of processes that control natural water composition is required for rational management of water quality. Interest in geochemistry of ground water has increased during the past decade as evidenced by hydrogeochemical studies which are becoming a firm part of regional hydrogeological studies. Hydrochemical study (or hydrogeochemistry) seeks to determine the origin of the chemical composition of ground water and the relationship between water and rock chemistry, particularly as they relate to ground-water movement.

Natural water composition is determined by chemical analyses, the data from which may be grouped and statistically evaluated. A considerable number of techniques and methods, based on differences in physical and chemical properties of water, are available to classify, compare, and summarize large volumes of data. The interpretive techniques and procedures do not require extensive application of chemical principles. Common procedures include simple inspection and comparison of chemical analyses, the preparation of graphs and maps, and more extensive statistical analysis. In the last decade, a number of computer programs for plotting and interpreting water-quality data have also been developed. Computer methods are most effective in storing, retrieving, and manipulating large volumes of data, and can minimize the mistakes in calculations and in plotting these large volumes in tables, graphs, and maps. This special subject, however, is not covered in this paper. A review of computer methods was published by Morgan et al. in *Ground Water* in 1966. Among others, the work of the members of the U. S. Geological Survey in Kansas deserves to be mentioned (Ropes et al., 1969).

The purpose of this paper is to review certain methods for interpreting water analyses, or for summarizing the water quality of an area under study, or illustrating water-quality characteristics on maps. Graphical, or other methods may not suffice completely to establish relationships sought by the hydrogeologist in a water-quality study. But such methods are valuable in pointing out features of analyses and arrays of data which need closer study. Generally, more detailed study of water-quality problems requires the participation of a geochemist.

Principles of graphical and numerical interpretation of chemical analyses of water are based on the relationship of ions, or groups of ions, forming a chemical type of water. A single graph will not give all of the information such as concentration of ions, comparison of the proportions of the ions, classification of water types, identification of mixed waters of different composition, identification of some of the chemical processes that may take place in ground-water circulation, or the relationship of chemical composition to rock type. The choice of presentation depends on the anticipated use and the type and quality of the analytical data. For purposes of discussion, applications of the methods are divided into four major sections: (1) classification, (2) correlation, (3) analytical and (4) illustrative. In each section, the methods are further divided and described according to the system used for plotting the analysis on a diagram or graph. There are five such systems: (1) numerical, (2) pointwise, (3) linear, (4) diagrammatical, and (5) areal expression. A summary of all methods is shown in Figure 16.

Complete analysis is required for most graphical representations. The concentration of constituents is expressed in milligrams per liter (mg/l) or parts per million (ppm); milliequivalents per liter (meq/l) or equivalents per million (epm); and in percentages of meq/l (or epm). In a complete analysis the total meq/l of anions should nearly equal the total meq/l of cations, or at least the two should be within 5 percent of each other. The analysis should be further adapted for graphical representation because in most instances only major constituents are shown. For this purpose potassium

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[a] Department of Geology and Geophysics, University of Wisconsin, Madison, Wisconsin 53706; presently on leave of absence from the Engineering-Geological and Hydrogeological Survey in Prague, Czechoslovakia.

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Chemical Analyses		No. 1 - Tertiary, Czechoslovakia			No. 2 - Upper Cretaceous, Czechoslovakia			No. 3 = Upper Cambrian, Wisconsin		
		mg/l	meq/l	meq%	mg/l	meq/l	meq%	mg/l	meq/l	meq%
C	Na^{+} K^{+}	266.2	10.68	68.24	1,913.7	81.54	70.24	7.9	0.34	4.4
A T	Mg^{2+}	21.9	1.80	11.4	132.8	10.95	9.41	43.0	3.54	45.6
I	Ca^{2+}	61.7	3.08	18.5	468.5	23.38	20.50	78.0	3.89	50.1
O	Mn^{2+}	traces	-	-	0.67	0.02	0.01	0.14	0.04	0.5
N	Fe	2.3	0.08	-	0.15	0.005	0.004	0.11	-	-
S	Σ	-	15.64	100.0	-	115.89	100.0	-	7.77	100.0
A	Cl^{-}	11.3	0.32	2.05	850.0	23.98	20.63	17.0	0.48	6.4
N	NO_3^{-}	0.0	-	-	0.0	-	-	0.7	0.0	0.1
I O	HCO_3^{-}	906.1	14.85	95.1	2,568.5	42.10	36.23	364.0	5.96	79.5
N	SO_4^{-}	21.2	0.44	2.82	2,406.5	50.10	43.11	50.0	1.04	13.9
S	Σ	-	15.61	100.0	-	116.18	100.0	-	7.50	100.0
TDS		929	-	-	8,343	-	-	480	-	-
Temp. °C		13.2	-	-	-	-	-	-	-	-
pH		7.5	-	CO_2	1,700	-	-	-	-	-
		mg/l	meq/l	meq %	mg/l	meq/l	meq%	mg/l	meq/l	meq %
Kurlov Formula		$M_{929}\frac{HCO3_{95}SO4_{3}Cl_{2}}{Na{+}K_{68}Ca_{19}Mg_{11}}T_{13.2}pH_{7.5}$			$M_{8,343}\frac{SO_{43}HCO3_{36}Cl_{21}}{Na{+}K_{70}Ca_{21}Mg_{9}}CO2_{1,700}$			$M_{480}\frac{HCO3_{79}SO4_{14}Cl_{6}}{Ca_{50}Mg_{46}Na{+}K_{4}}$		
Type of water		Alkali - Bicarbonate			Alkali - Sulfate - Bicarbonate			Calcium - Magnesium - Bicarbonate		

Fig. 1. Data from chemical analyses used as demonstrations in graphs.

and sodium are usually grouped together, and fluoride and nitrate are grouped with chloride, depending upon water type and purpose of the study. The composition of the water can then be expressed in terms of 3 cationic and 3 anionic species. An example of the way water data are arranged for graphical representation is shown in Figure 1. These data are also used as demonstrations in plotting the presented graphs.

CLASSIFICATION METHODS

Classification methods are used for basic characterization of the chemical composition of ground water. Such methods differentiate chemical types of water and help identify the dominant types. Numerical and pointwise systems of representation are used primarily. Pattern diagrams are of subordinate importance because of their unsuitability for handling large volumes of data.

A very useful method for primary characterization of the chemical composition of water is the Kurlov formula (1928). Chemical composition is expressed by a quasifraction with anions and cations in the numerator and denominator, respectively. Analyses are shown in descending order of concentration, and the sums of anions and cations are each taken as 100 percent of meq/l. All components are considered which have concentrations greater than 1 percent of the total meq/l. Each chemical symbol is subscripted to represent its percentage of the total meq/l. Total dissolved solids, expressed in mg/l (or g/l) precede the fraction as a constant M (mineralization), and other characteristic constituents or properties of the water, such as trace elements of higher concentration, pH, or temperature follow the fraction. Examples of Kurlov formulae are given in Figure 1. The descending arrangement of ions in the formula enables us to rapidly recognize the basic water type. In designating the water type, only those constituents are considered which amount to more than 25 percent of the total meq/l. The Kurlov formula can be used for basic characterization of water composition in tables or on maps. It is useful for general classification and as a basis for graphical methods and further interpretation.

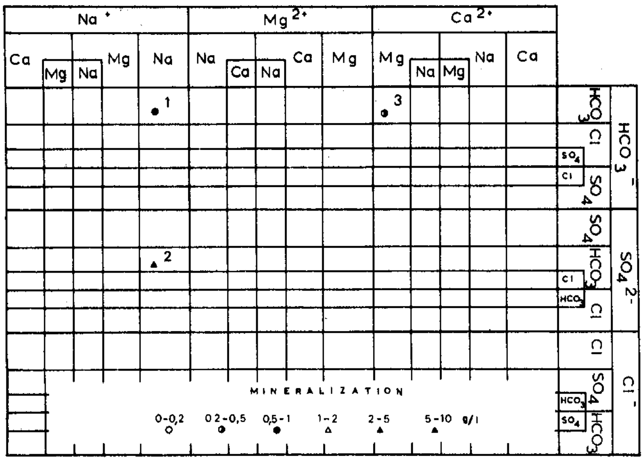

Fig. 2. Vostroknutov's tabular graph.

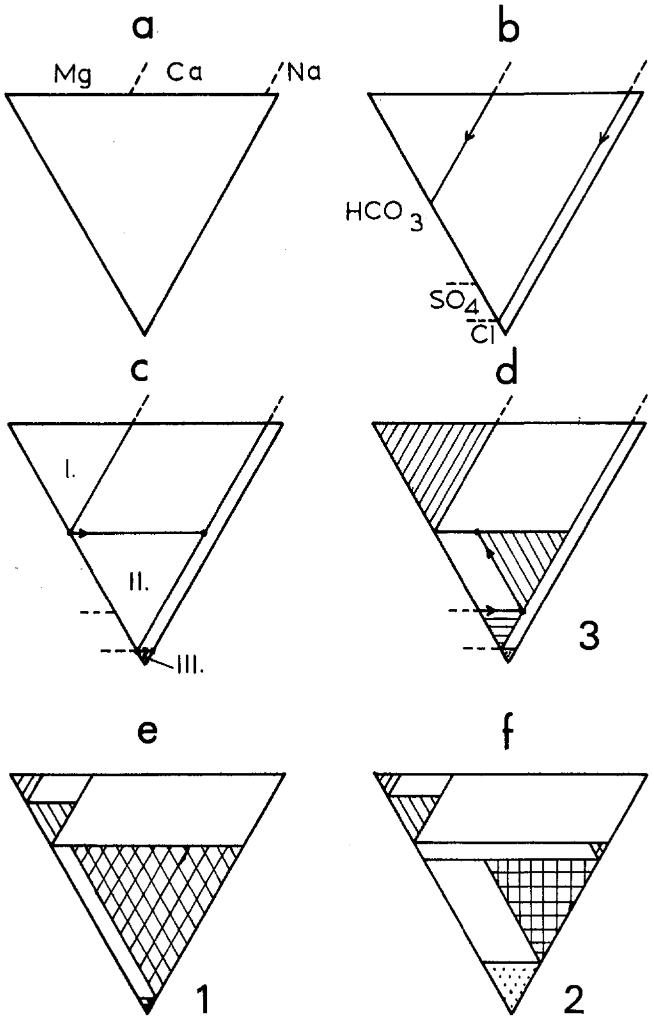

Fig. 3. Durov's triangular diagram. Each side of the triangles is equal to 100 percent meq/l. Chemical analysis No. 3 was used as an example in constructing the diagram: (a) and (b) first step, (c) second step, (d) third step, (e) resulting diagram of the analysis No. 1, and (f) resulting diagram of the analysis No. 2.

Another useful classification method is the tabular graph, developed by Vostroknutov (Figure 2). The graph shows the distribution of selected chemical types of water in a given range of mineralization, and their relationship to hydrogeological units, by the use of different symbols and colors for plots. Chemical analyses are plotted as points in appropriate boxes of the graph, considering only those constituents which exceed 25 percent of the total meq/l. Classification of water type can be done in the same manner as in the Kurlov classification, i.e. each box indicates one type of water. Vostroknutov's graph is particularly useful for statistical purposes when large volumes of data are compared.

More complete characterization of ground water can be achieved by the use of a triangular diagram proposed by S. A. Durov (1948). The diagram consists of an inverted equilateral triangle (Figure 3). Each full triangle edge equals 100 percent meq/l. Cations are plotted on the top, horizontal edge from left to right in the order: Mg, Ca, and Na + K. Anions are plotted on the left edge from top to bottom in the order: $HCO_3 + CO_3$, SO_4 and Cl. The procedure for constructing the diagram shown in Figure 3 is as follows: The cations are plotted, after which parallels to the lower right side of the diagram are drawn, dividing the triangle into three cation zones. The anions are similarly plotted. The next step is to draw lines from points of intersections of the cation lines with the lower left side of the diagram inside corresponding cation zones and parallel to the upper side of the diagram, thereby producing three auxiliary triangles (I, II, III). The representative triangles are then separated from the auxiliary ones by drawing the anion lines to points of intersection with the cation lines, from whence parallel lines to the lower left side of the diagram are drawn to the nearest horizontal line. The final products are three to five representative triangles which can be emphasized by hatching. Each pattern of hatches represents one hypothetical combination of salts. For analysis No. 3, used as an example in constructing the diagram in Figure 3, there are one Mg salt (bicarbonate), two Ca salts (bicarbonate and sulfate), and one alkali salt (chloride) in the diagram. Similarly, analyses No. 1 and 2 are plotted to yield five hypothetical salts each.

The hypothetically combined salts, of course, do not necessarily correspond to the real conditions in the solution. Therefore, we cannot make any conclusion with respect to the chemical processes involved. The hypothetical salt groups are established only for the purpose of classification insofar as they represent groups of chemical types in which the respective ions are principal constituents.

Advantages of this diagram include relatively simple construction, its instructive illustration of possible combinations of ions, and the sensitive expression of the relationship of cations and anions. Durov's diagram is also useful for correlation of chemical analyses, and in some instances also for illustrating chemical compositions on maps.

Durov used the diagram as a basis for classifying ground water according to chemical type (1949). He distinguished 18 types of water, grouped into five classes on the basis of genetic interrelations. Detailed description and geneses of waters of each class and type were published in 1959, as follows:

Class I (types 1-3)—the simplest or primary waters of very low concentration (100-300 mg/l); bicarbonates of Ca and Mg are predominant salts.

Class II (types 4-6)—secondary (transition) types of water resulting from waters of the first class enriched by soluble SO_4 and Cl salts of Mg and alkali; mineralization increases to 500-1,000 mg/l.

Classes III, IV and V—complex types formed from the waters of class II. The chemical composition is a result of both solubility and the loss of some constituents (III—removal of HCO_3, IV—removal of HCO_3 and SO_4, V—loss of Ca, Mg and SO_4). Class III (types 7-10) includes sulfate waters and acid mine waters with free H_2SO_4. Class IV (types 11-15) are chloride waters, which appear to be the most stable. Class V (types 16-18) are alkaline bicarbonate waters of low mineralization and low hardness.

A review of Durov's classification was published by G. V. Chilingar (1956).

In general, classification procedures are a basis for grouping waters that are closely related to each other. Usually, classification is done by simple inspection of a group of chemical analyses and separating them into obviously interrelated subgroups. Designation of the water type is based on the predominant cations and anions, which are commonly expressed in percent meq. The name of the water type should be considered carefully to prevent it from becoming misleading. A water is usually of a mixed type and should be identified by the names of all important cations and anions and not only by the names of the principal constituents. Usually all ions whose percentage composition equals or exceeds 25 percent of the total meq are used in formulating the name.

Classification is preliminary to further study of genetic reasons for compositional differences of water. The term classification as used in this paper means classification of a given volume of water analyses in the area under study for special purposes; not classification of ground water in general. Many classification systems used for interpreting chemical composition of water can be found, especially in German and Russian literature. At least the basic ones should be mentioned: C. Than (1890), E. Hintz and L. Grünhut (1907), V. A. Sulin (1935), and O. A. Alekin (1953). Extensive review of various classifications is given by N. Konzewitsch (1967). In United States literature relatively minor attention has been paid to the classification of waters. Among the oldest methods, the geochemical classification schemes of Palmer (1911) and Hill (1940) are of some interest.

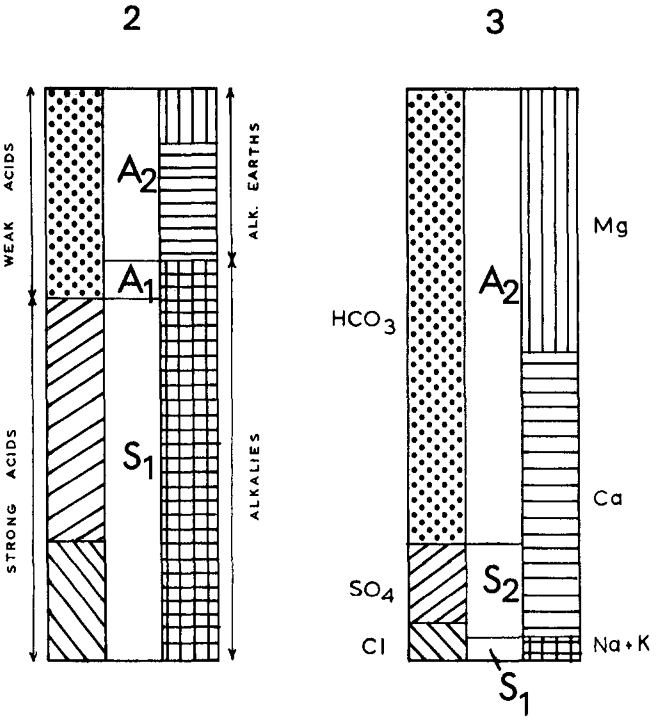

Fig. 4. Palmer-Rogers graph. A_1, A_2, S_1, S_2 = Palmer's characteristics. Ion-concentration patterns, see Figure 9.

Palmer (1911) divided natural waters into five classes on the basis of six special characteristics: (1) Primary salinity (alkali salinity)—S_1, formed both by salts of strong acids and strong bases; (2) Secondary salinity (permanent hardness)—S_2, formed by salts of strong acids and weak bases; (3) Tertiary salinity (acidity)—S_3, formed by salts of strong acids and metals; (4) Primary alkalinity (permanent alkalinity)—A_1, formed by salts of weak acids and strong bases; (5) Secondary alkalinity (temporary alkalinity)—A_2, formed both by salts of weak acids and weak bases; and (6) Tertiary alkalinity—A_3, formed by salts of weak acids and metals.

Graphical representation of Palmer's characteristics was introduced by R. G. Rogers (1917a). He developed the diagram (1917b), called the Palmer-Rogers diagram (Figure 4). It has three columns: (1) left column expresses the ratio of strong and weak acids; (2) right column expresses the ratio of strong and weak bases, and metals; and (3) the middle column gives the salinities and alkalinities.

Hill's original diagram (1940) consists of anion and cation triangles which occupy positions at lower left and lower right, respectively, with bases aligned vertically, with the vertices pointing toward each other. The upper central portion of the diagram is diamond shaped (Figure 5). The intersections of the projections of anions and cations

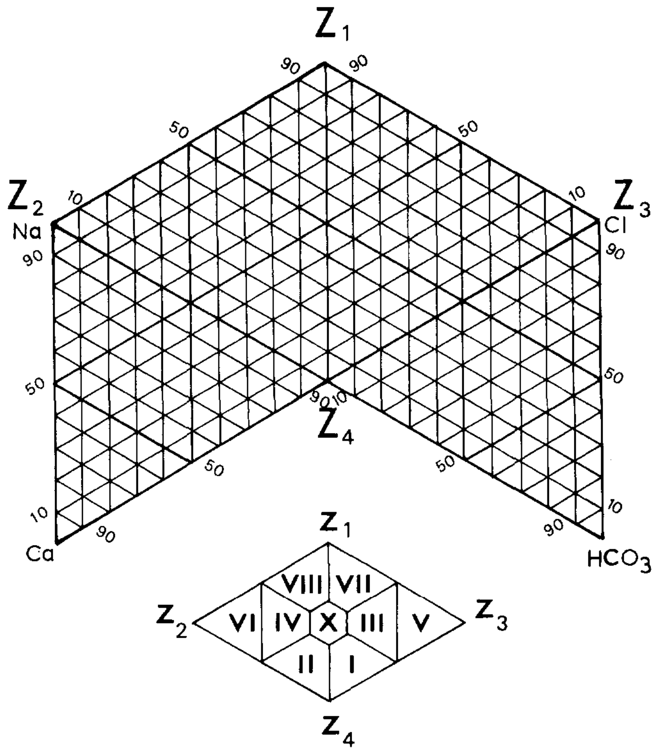

Fig. 5. Hill's diagram. Original diagram developed in 1940. Each side of the triangles is equal to 100 percent meq/l.

(plotted in the lower triangles in percent of total meq) in the central field represent the composition of the water. Hill divided the diagram into nine types of water.

W. Back (1961) classified waters in the northern part of the Atlantic Coastal Plain into eight hydrochemical facies. Trilinear diagrams were used in his study (1966) for subdividing facies into chemical types of water on the basis of dominant ions.

CORRELATION METHODS

Correlation methods are used for comparing chemical analyses in order to find differences or similarities in water composition. Most convenient are methods utilizing linear and numerical systems, although patterned diagrams are also used.

One of the best techniques for showing correlation among types of waters is the expression of the relationship among ions, or of one constituent to the total concentration, in terms of mathematical ratios. For comparison, the concentrations are expressed in mg/l or meq/l. Fixed rules regarding selection of values to be compared by ratios cannot be given. The ratios are selected according to the characteristic composition of both rocks and water, sources of the ions, and expected chemical behavior.

The ratio of calcium to magnesium may be useful in studying water from carbonate rocks. The ratio of sodium to total cations is useful in sediments having cation exchange properties. The ratio of sodium to total cations is useful in sediments having cation exchange properties. The ratio of chlorides to other ions may be useful in studies of seawater intrusion or brine contamination. Ionic ratios are especially useful in studies of oil-field waters. D. E. White (1960) proposed a set of median ratios of critical components to assist in determining the origin of deep waters. Ratios utilized in the study are Ca/Na, Mg/Ca, K/Na, Li/Na, HCO_3 + CO_3/Cl, SO_4/Cl, F/Cl, Br/Cl, I/Cl, and B/Cl.

Comparison of analyses using ionic ratios has many undeveloped possibilities other than correlation. They can be used for classification schemes and for genetic studies of deep waters. The alkali and halogen groups, as well as boron, are of particular interest in genetic studies because in general they are highly soluble. The quantities present in water are determined by the local supply of each element throughout the history of origin and migration of the water.

Another method of correlation utilizes linear graphs. The best known graphs using arithmetic or logarithmic scales for expression of water quality data are those of French water chemists R. Frey and H. Schoeller. The nomograph proposed by Schoeller (1935) depicts a group of analyses on equidistant verticals, the number of which depends on the number of constituents being expressed. Besides ion concentrations, plotted on a logarithmic scale, we can plot other properties of the water such as pH, total dissolved solids, alkalinity, acidity, and temperature. Scales for these additional constituents or properties are optional and usually arithmetical. By joining points on all vertical lines an analysis is shown as a characteristic broken line which represents chemical composition of the water. Lines of different types (dashed, dotted, solid, etc.) are chosen for distinguishing individual analyses. Waters of similar composition plot as near-parallel lines. This graph is especially useful for comparing waters of low concentration and waters which do not differ greatly in concentration. Schoeller's nomograph was modified by R. C. Vorhis of the U. S. Geological Survey and is widely used in North America. The revised nomograph has the advantage of showing also the relationship among mg/l and meq/l for different ions. Each vertical has its own scale in mg/l and the corresponding scale in meq/l is on each side of the diagram. Analogous to Schoeller's nomograph is a diagram proposed by R. Frey (1933), who used an arithmetical scale for plotting.

Included in correlative methods is a cumulative percentage plot of analyses in mg/l. Types of water are differentiated on the basis of the slope of the profile formed by joining the successive points.

Changes in composition of ground water with depth can be compared using a linear graph proposed by G. S. Rogers (1917b). The depth of aquifers was plotted on a vertical line, and the ion concentration, in mg/l or meq/l, on a hori-

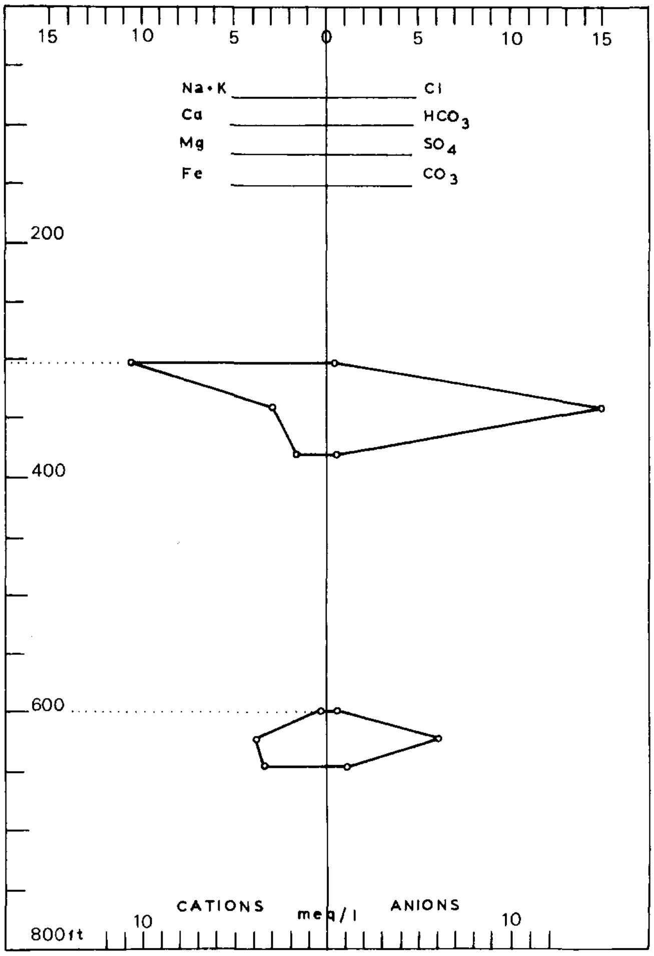

Fig. 6. Stiff pattern diagram. Fe and CO_3 may be plotted on the fourth line if applicable.

zontal line for each aquifer. A broken line connecting a constituent in each aquifer represents its change with depth.

A more sophisticated method for demonstrating vertical changes in the chemical composition of water is that of H. A. Stiff (1951). The basis of Stiff's system is a vertical line which has two functions. It is both a depth scale of aquifers and vertical zero axis from which the concentrations of ions are plotted on four parallel horizontal axes extending on each side. Examples of the resulting irregular patterns are shown in Figure 6. Each different pattern represents a different type of water. The width of the pattern could be used as an approximate indication of total ionic content.

The Stiff system is a relatively distinctive method of showing differences or similarities in waters and changes in water composition with depth. It is useful especially for illustrating chemical composition in hydrogeological cross sections. It can be used also for classification purposes, and is useful as a symbol on a map. Graphical schemes useful for correlation include also Collin's bar graph (1923) and the Rónai starred diagram (1958) which will be discussed later.

ANALYTIC METHODS

Methods used to identify the origin of the water, and to determine the processes involved in natural water chemistry are based mostly on numerical, pointwise and linear systems of expression of the analysis.

Among numerical methods, the coefficient $K\frac{CO_3}{Cl}$, which is the ratio of carbonates and bicarbonates to chloride in meq/l is used in genetic studies of oil-field waters. Its value is a function of depth, assuming that in shallow aquifers the oxygeneous ions (HCO_3, SO_4) are relatively abundant compared to chloride, whereas in deep aquifers the converse is true. Also other ionic ratios described in the previous section may be used for genetic studies.

In the study of oil-field waters, Palmer's characteristics are sometimes applied, as discussed above. On the basis of Palmer's characteristics, L. Gráf (1963) proposed a simple graph which, in addition, shows total dissolved solids. The graph utilizes rectangular coordinates with total dissolved solids plotted in mg/l on the abscissa. Constituents of individual analyses are plotted in meq percent on verticals, distances of which from the zero axis correspond to total concentration.

The most important methods for genetic studies of ground water are those in which a chemical analysis is plotted as a point. Both trilinear and rectangular plots can be used. The trilinear plots are much more effective and are used nowadays almost exclusively.

Rectangular plotting systems were widely used in past geochemical studies. They include the diagram proposed by H. Harrasowitz of Germany (1931), further elaborated on and improved by N. N. Tolstichin of Russia (1932, 1934, 1937). The main disadvantage of this diagram, as well as other similar ones, is its limitation to four constituents. The carbonates are usually lumped together with sulfates, and Ca with Mg.

A diagram of historical interest is one by Langelier and Ludwig (1942), in which cations are plotted on the ordinate and anions on the abscissa in percent.

A revival of rectangular plots is indicated by the system proposed by L. A. Simanovski (1963) which used the vector graph of N. A. Zavaricki for chemical studies of igneous rocks. The anions are plotted horizontally and the cations vertically, both in meq/l percent. The starting point (HCO_3 + Ca) is plotted from the upper left corner, the final point of the vector (Cl + Na, K) from the lower right corner of the diagram. Concentration of SO_4 and Mg is expressed by the length and inclination of the vector. Total concentration can be distinguished by use of different symbols at points of origin.

The trilinear plots utilize two triangles (Ferré triangles, known from Niggli's classification of igneous rocks), one for anions and one for cations. Each vertex represents 100 percent of a selected ion or group of ions. Hem (1970) stated that the earliest reference to trilinear plots was by W. H. Emmons and G. L. Harrington (1913), who used the triangles for comparison of mine waters with hot-spring waters.

A considerable number of authors have described trilinear plots in which the cation and anion triangles are combined in several ways. The expression of an individual analysis by two points on separate graphs was found inconvenient. Therefore anion and cation fields were combined to allow expression of an analysis as a single point in a two-coordinate diagram.

The first diagram published in the United States incorporating this combination was that of Hill (1940), which has been mentioned already.

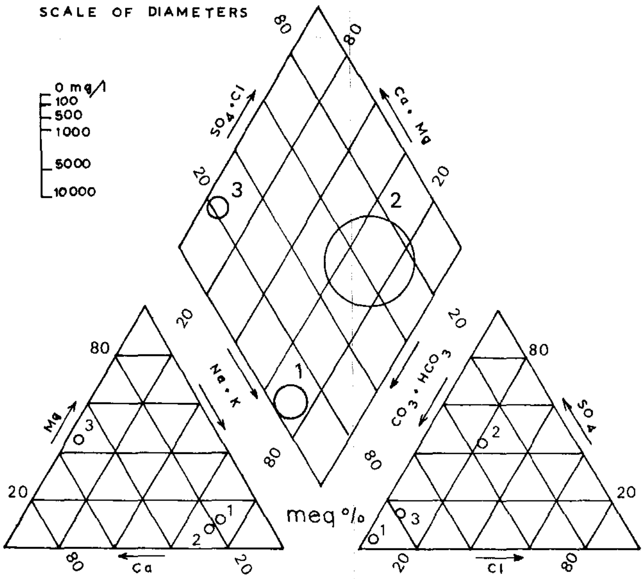

Fig. 7. Piper diagram. Trilinear diagram proposed by Piper and modified by Hill as now being used.

A. M. Piper (1944) independently developed a diagram similar to Hill's diagram (Figure 7). This diagram with minor changes is now widely used in the United States. The points plotted in the central diamond-shaped field may have areas proportional to total concentrations, and are located by extending the points in the anion and cation triangles to the points of intersection. The first version was used in 1942 and modified in 1953. The history of Piper's and Hill's diagrams is a good example of difficulties which may arise when two authors develop essentially similar diagrams at the same time, and how difficult it is to trace the origin of the diagram. Publication of Piper's original diagram in 1944 provoked a long discussion. Actually, Piper's diagram in the version now used is a Hill's modification from 1944 (Am. Geoph. Union Trans., v. 25, pp. 924-925).

Some of the shortcomings of trilinear plots are removed in the double triangular diagram proposed by S. A. Durov (1948). The basis, once again, is percentage plotting of cations and anions in separate triangles (Figure 8). The intersection of lines extended from the points to the central rectangular field gives a point representing a type of water. From that point, lines drawn to adjacent rectangles give points showing total concentration (scale in mg/l or g/l) and any other optional characteristic constituent of the water (in mg/l). Ions of lesser importance to the problems studied are usually located at the vertices of triangles farther from the central field.

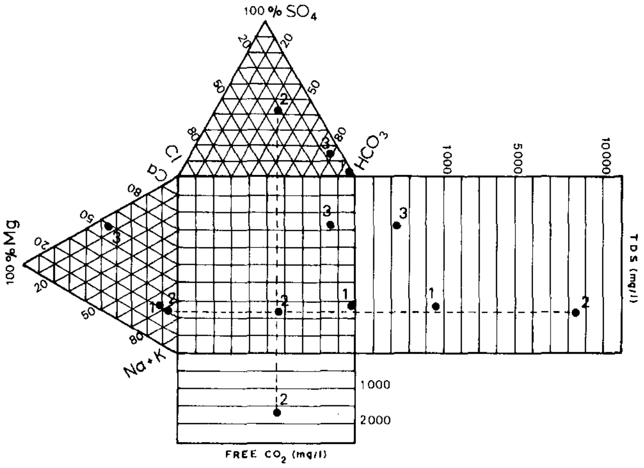

Fig. 8. Durov's doubled triangular diagram. Each side of the triangles is equal to 100 percent meq/l.

Durov (1950) further improved his diagram to permit analysis of chemical composition and total dissolved solids. His double tetrahedral diagram utilizes a system of rectangular projections of spatial dimensions in the plan. The spatial expression removes the restriction of a geometrical expression. Although not convenient for common use in reports of investigation, it can be used in special genetic studies of the origin of chemical composition of water.

Constituting a special category of analytical methods are computer methods which are very useful for sorting large groups of data according to multiple criteria, for calculation of statistical values, and for graphic comparison. The members of the U. S. Geological Survey in Lawrence, Kansas have developed programs for two standard methods for interpreting ground-water analyses—the Stiff diagram and the Piper diagram (Kansas State Geol. Survey Special Distribution Publ. No. 43 and 45 respectively, 1969). Besides that, L. H. Ropes and others (1969) have developed a special program for FORTRAN IV. Two semilog graphs are produced on the line printer. The two graphs represent front and top orthographic projections of a three-dimensional array of data. The principal graph is a two-dimensional plot of parameters versus concentration on parallel horizontal log scale axes. A second optional graph (called the top view) contains a horizontal log scale exactly as in the principal graph, but individual samples are spaced along the vertical axis, which is the time or space axis. Constituents are plotted either in meq/l or mg/l. Rope's graph can be used for analyses of the data or for graphic display.

SYNTHETIC AND ILLUSTRATIVE METHODS

Special methods are used for representation of water quality on maps or for display purposes. Most useful for these purposes are pattern diagrams and linear and areal methods.

The simplest method but least descriptive is a number at the well symbol representing concentrations of characteristic constituents in mg/l. Somewhat better is the use of the Kurlov formula, if the scale of the map permits.

The technique of mapping ground-water quality characteristics by drawing lines of equal concentration of dissolved solids or of single ions has been commonly used for years. Such isogram maps extrapolate data between sampling points and thus accuracy is a function of sampling points density.

A related procedure identifies concentration ranges or certain types of water by areal expression using either color, shading, or hatching. Hatches can illustrate both chemical type of water and degree of concentration by different patterns and thicknesses of lines (Figure 9). Colors can be similarly used; the concentration ranges are differentiated by color shades, and different types of water by different colors.

Water quality may be illustrated on a map by use of symbols, usually consisting of various pattern diagrams.

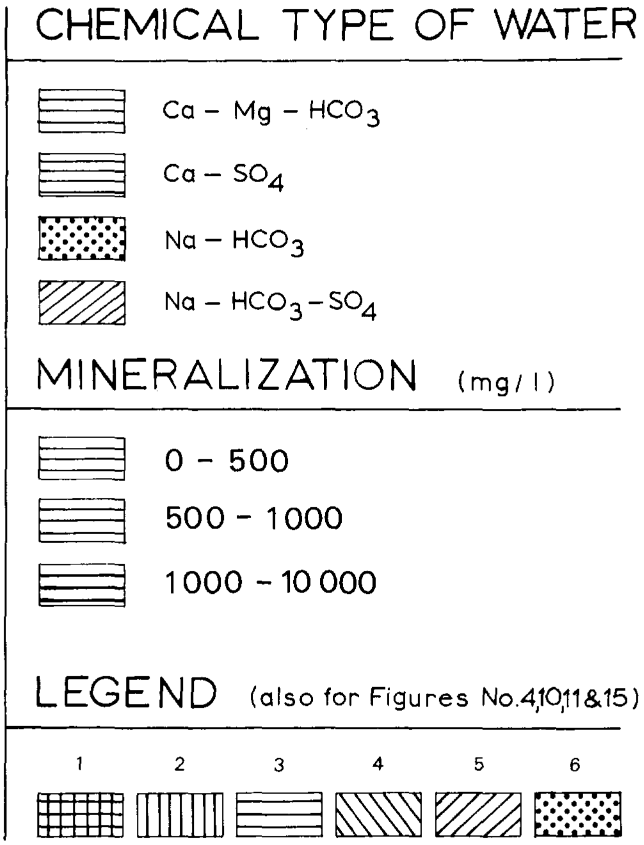

Fig. 9. Areal representation of water quality. Example of the expression of chemical type of water and salinity on maps. Legend applies also for Figures 4, 10, 11, and 15:

1. Alkali – $Na^+ + K^+$
2. Magnesium – Mg^{2+}
3. Calcium – Ca^{2+}
4. Chloride – Cl^-
5. Sulfate – SO_4^{2-}
6. Carbonates – $HCO_3^- + CO_3^{2-}$

Bar graphs, besides their use as symbols, are very illustrative for oral or written reports on water quality. The German scholars, W. Petraschek (1904) and E. Hintz (1907), are believed to have originated the bar graph, which was then a favorite method of representation of water quality in absolute units. There are a number of various graph types although most of them are only of historical interest.

The bar graph most widely used in the United States is that by W. D. Collins (1923). The bar is divided into two vertical columns whose heights are proportional to the total concentration of cations in the left column, and of anions in the right column, both in meq/l (Figure 10). The concentrations of ions are emphasized by distinctive colors or patterns. In descending order, six column divisions are typically used: Na + K, Mg, Ca for cations, and Cl + NO_3, SO_4, and CO_3 and HCO_3 for anions. The constituents can be plotted also in percent meq. The Collins' diagram is an effective visual tool in oral presentations of water composition.

A bar proposed by C. E. Reistle, Jr. (1927) consists of one vertical column whose height is proportional to the total concentration of ions in ppm. Zero is in the middle. Concentrations of cations represent the upper half and concentrations of anions represent the lower half of the diagram.

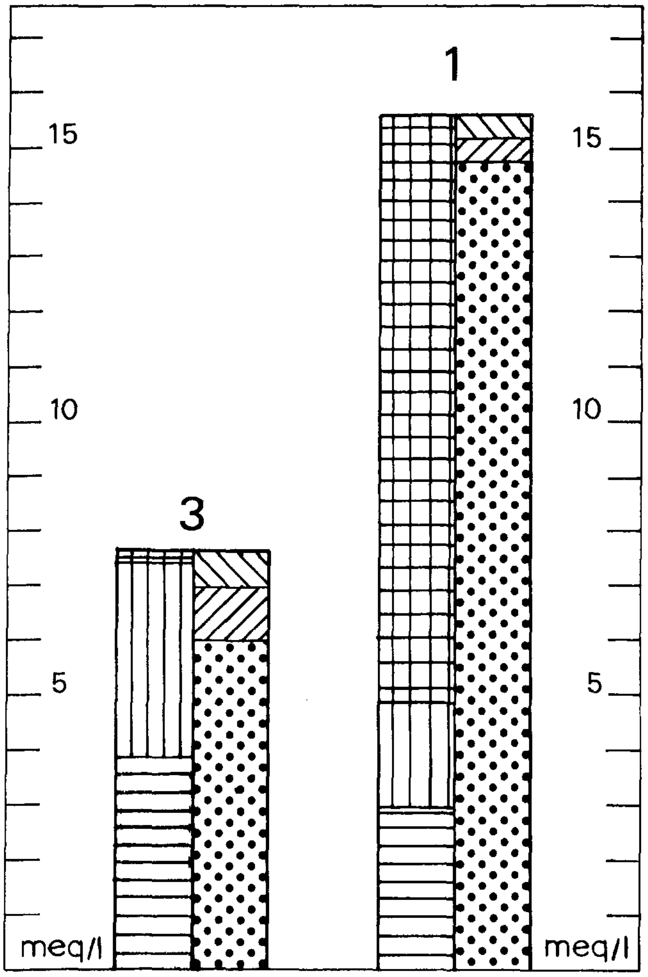

Fig. 10. Collin's bar graph. Ion-concentration patterns, see Figure 9.

The simplest of pattern diagrams are circular diagrams which are primarily used as symbols on maps. There are many types of such diagrams, the most common being the so-called pie diagram (Figure 11a) in which subdivisions of the area represent proportions of different ions in percentage of meq/l. The cations are in the upper half and anions are in the lower half of the circle, each usually taken as 100 percent. The pie diagram can be drawn with a scale for the radii which makes the area of the circle represent the total ionic concentration. Or the total concentration can be given as a number at the symbol.

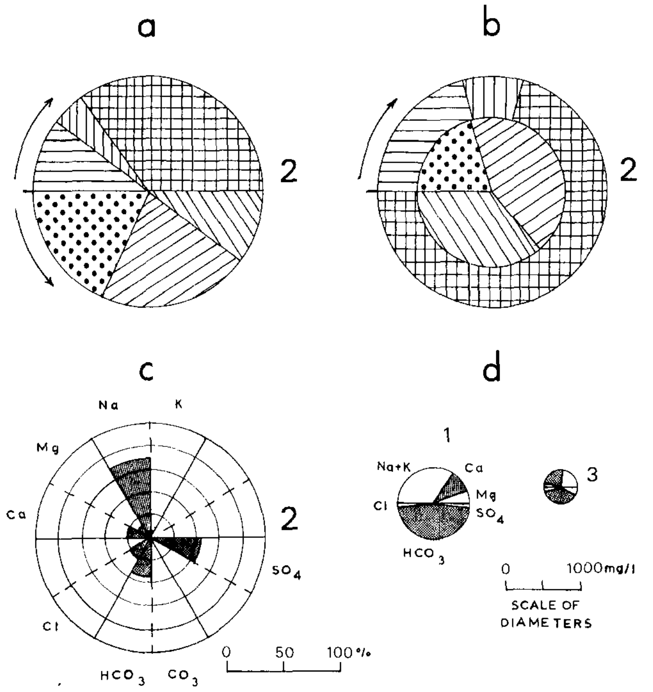

Fig. 11. Circular diagrams. Ion-concentration patterns, see Figure 9. a—"Pie" diagram. Upper half of the circle is equal to 100 percent meq/l of cations, lower half of the circle is equal to 100 percent meq/l of anions. One percent of meq/l is equal to 1.8° of the circle; b—Tolstichin cyclical diagram. Outer annulus is equal to 100% of cations, inner circle is equal to 100 percent meq/l of anions. One percent of meq/l = 3.6°.

Only a little different is the cyclical diagram proposed by N. J. Tolstichin (1937). The outer annulus is equal to 100 percent meq cations whereas the inner circle represents 100 percent meq anions (Figure 11b). Ionic concentrations are emphasized by different colors or patterns.

In Czechoslovakia, a disk diagram is used which can show more than six ions (Figure 11c). Concentrations are plotted in percent meq.

Circular diagrams can complicate the legibility of a map, especially when many sampling points are available, or when used on small scale maps. Small diameter diagrams usually are difficult to construct and read. A small modification used by the Central Geological Institute in Czechoslovakia enables the hydrogeologist to use this diagram for diameters as small as 3 mm. Instead of patterns or colors, black is used for the central portion of halfcircles (concentration of Ca in cations, and concentration of carbonates in anions).

Many other pattern diagrams are used as symbols on a map. In the diagram proposed by F. G. Tickell (1921) ion concentrations are plotted in percentages of meq/l on a symmetrical system of six radiating axes formed by joining the vertices of a regular hexagon (Figure 12). The points on individual axes are connected and the result is an irregular pattern which may be made more distinctive by shading. Tickell used originally only five axes, leaving one axis for any other constituent of a diagnostic value. In the modern version of his diagram, all axes are regularly used (Figure 12c). The total concentration is not expressed in the diagram, but it can be entered as a number at the symbol. Z. Dalmady (1928) modified Tickell's diagram by using thicker lines on respective axes (Figure 12d).

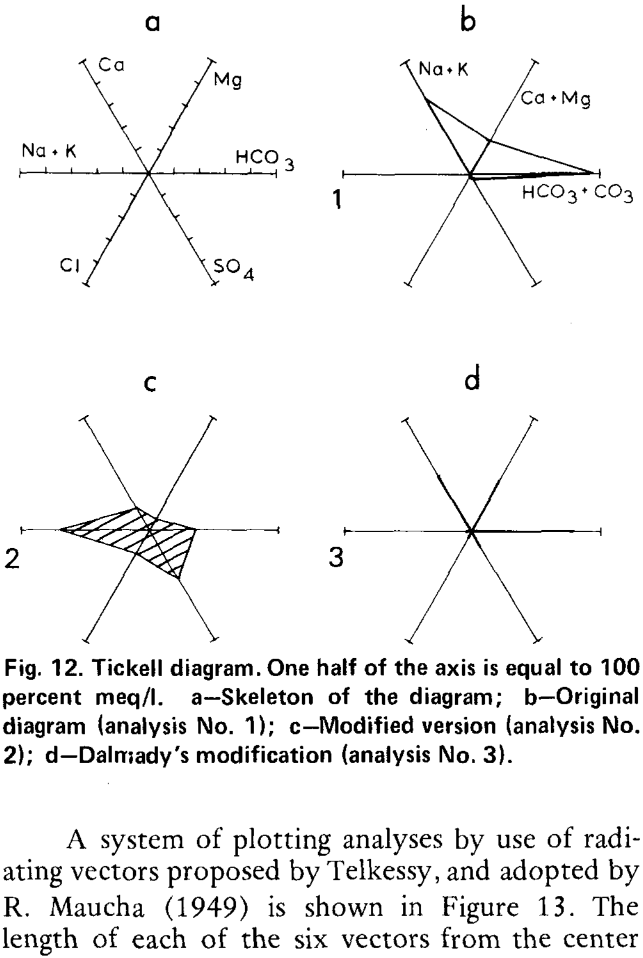

Fig. 12. Tickell diagram. One half of the axis is equal to 100 percent meq/l. a—Skeleton of the diagram; b—Original diagram (analysis No. 1); c—Modified version (analysis No. 2); d—Dalmady's modification (analysis No. 3).

A system of plotting analyses by use of radiating vectors proposed by Telkessy, and adopted by R. Maucha (1949) is shown in Figure 13. The length of each of the six vectors from the center represents the concentration of six major ion groups.

B. R. Colby, C. H. Hembree, and F. H. Rainwater (1956) used a pattern diagram in which four ionic groups are plotted on rectangular coordinates in meq/l. By connecting the points on coordinates, a kite-like figure results which can be used as a symbol on a map (Figure 14).

All diagrams described so far have one common disadvantage. The expression of values is

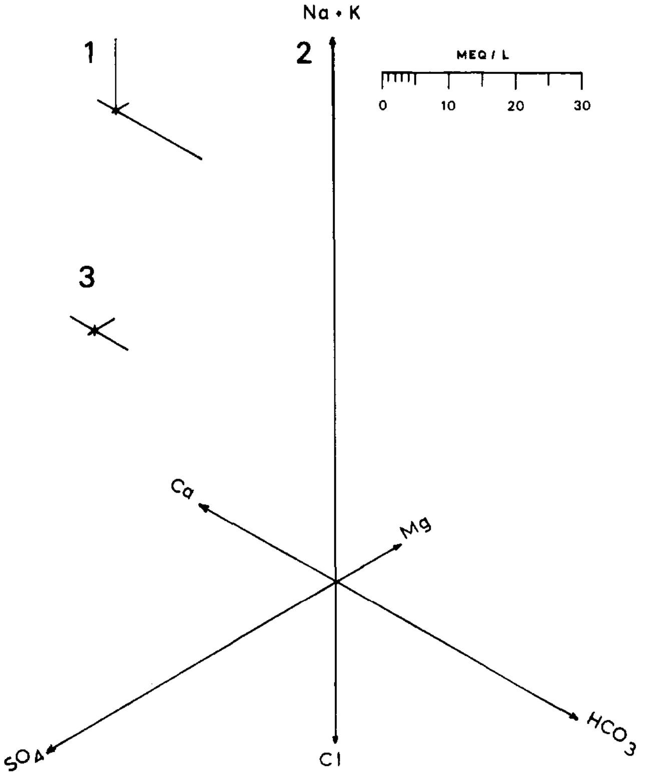

Fig. 13. Maucha vector diagram.

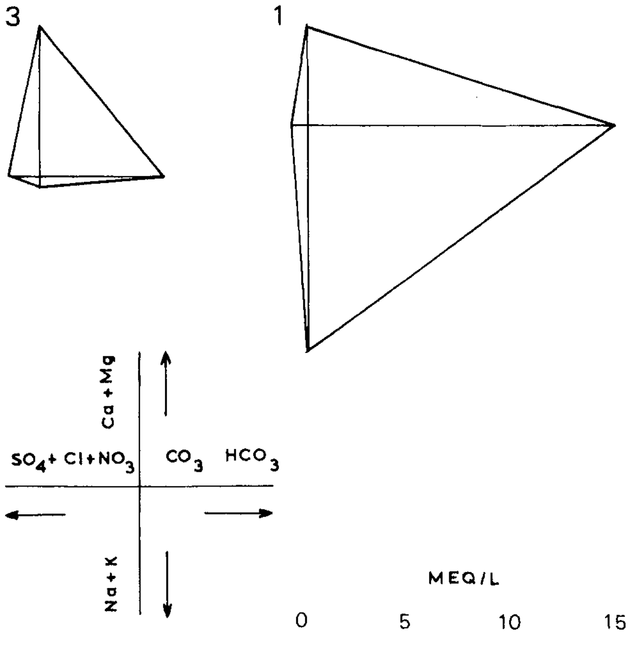

Fig. 14. "Kite" diagram (after Colby, Hembree, and Rainwater, 1956).

linear and thus they lack sensitivity for constituents in small concentration or for showing small changes in chemical composition. This disadvantage is not inherent in diagrams with quadratic expressions of values. In these, the constituents are expressed areally in two dimensions and the sensitiveness of the diagram increases with the square of the diameter.

An example is the starred diagram proposed by A. Rónai (1958). The skeleton of the diagram is

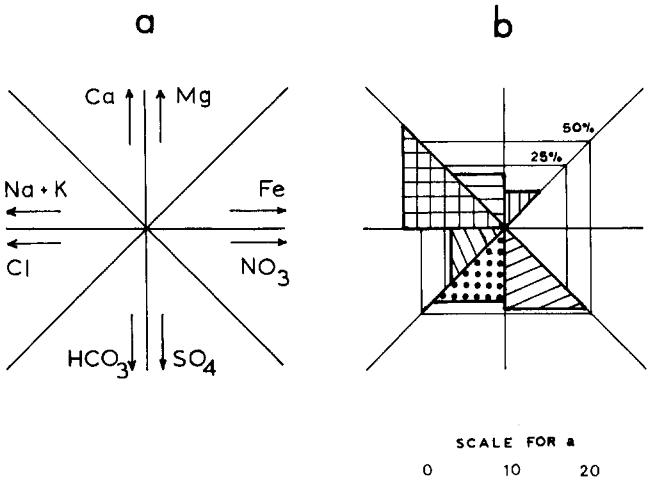

Fig. 15. Rónai starred diagram. Ion-concentration patterns, see Figure 9. a—System for plotting the analysis; b—Graphical representation of the chemical analysis No. 2 by using Table 3. Scale for coefficient a is optional.

Table 1. Conversion Factors for Plotting the Analyses in Rónai Diagram (after J. Jetel, 1963)

c	a	c	a	c	a	c	a
0,1	0,47	9,5	4,35	28,0	7,47	63,0	11,22
0,2	0,63	10,0	4,47	29,0	7,61	64,0	11,31
0,3	0,77	10,5	4,58	30,0	7,74	65,0	11,40
0,4	0,89	11,0	4,69	31,0	7,86	66,0	11,49
0,5	1,00	11,5	4,80	32,0	8,00	67,0	11,58
0,6	1,10	12,0	4,90	33,0	8,12	68,0	11,66
0,7	1,18	12,5	5,00	34,0	8,24	69,0	11,75
0,8	1,26	13,0	5,10	35,0	8,36	70,0	11,84
0,9	1,34	13,5	5,20	36,0	8,47	71,0	11,91
1,0	1,41	14,0	5,25	37,0	8,59	72,0	12,00
1,1	1,48	14,5	5,38	38,0	8,71	73,0	12,09
1,2	1,55	15,0	5,46	39,0	8,82	74,0	12,15
1,3	1,61	15,5	5,56	40,0	8,94	75,0	12,22
1,4	1,67	16,0	5,65	41,0	9,05	76,0	12,32
1,5	1,73	16,5	5,75	42,0	9,16	77,0	12,41
1,6	1,79	17,0	5,83	43,0	9,26	78,0	12,50
1,7	1,84	17,5	5,91	44,0	9,37	79,0	12,57
1,8	1,90	18,0	6,00	45,0	9,49	80,0	12,66
1,9	1,95	18,5	6,08	46,0	9,59	81,0	12,72
2,0	2,00	19,0	6,16	47,0	9,69	82,0	12,80
		19,5	6,24	48,0	9,79	83,0	12,90
2,5	2,24	20,0	6,32	49,0	9,90	84,0	12,97
3,0	2,45	20,5	6,40	50,0	10,00	85,0	13,03
3,5	2,64	21,0	6,47	51,0	10,10	86,0	13,11
4,0	2,83	21,5	6,55	52,0	10,20	87,0	13,19
4,5	3,00	22,0	6,63	53,0	10,30	88,0	13,28
5,0	3,16	22,5	6,71	54,0	10,40	89,0	13,35
5,5	3,22	23,0	6,78	55,0	10,50	90,0	13,42
6,0	3,46	23,5	6,85	56,0	10,58	91,0	13,50
6,5	3,60	24,0	6,92	57,0	10,68	92,0	13,58
7,0	3,74	24,5	7,00	58,0	10,77	93,0	13,64
7,5	3,87	25,0	7,06	59,0	10,86	94,0	13,71
8,0	4,00			60,0	10,95	95,0	13,79
8,5	4,12	26,0	7,20	61,0	11,05	96,0	13,85
9,0	4,24	27,0	7,35	62,0	11,12	97,0	13,92

c = ion concentration in meq/l
a = coefficient for plotting data in the graph

formed by eight radiating axes on which rectangular equilateral triangles are drawn. The areas of triangles represent the concentrations of each ion. The cations (Na + K, Ca, Mg, and one optional) are in the upper half, and the anions (Cl, $HCO_3 + CO_3$, SO_4 and one optional) are in the lower half of the diagram; both are plotted in coefficients equivalent to meq/l (Figure 15). The size of the diagram is proportional to the total concentration. The construction of the diagram is very simple by use of a modification proposed by J. Jetel (1963) of Czechoslovakia. The data necessary for plotting the analyses are shown in Table 1.

The methods and techniques presented here for representation of water-quality data are far from complete. This paper is not intended to cover all the methods that have been suggested in the literature which would be an impossible task. A considerable number of authors have introduced new graphs and diagrams, or modifications and adaptations of the old ones. Many of the techniques were proposed for a single purpose and are of little use for other purposes. An attempt has been made here to point out methods which are, at present, considered to be most useful, and to discuss them successively as to their possible use. Almost every method, however, has several uses. Each of them has been put in the category where its use seems to be predominant. A summary of all methods is shown in Figure 16. Mentioned also are methods of historical interest which document the development of modern methods for interpreting water-quality data. Explanation of the methods not published in American literature is emphasized because they are not readily available for common use.

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System of plotting analysis Use of method	Numerical	Pointwise	Linear	Pattern diagrams		Areal
				Irregular shape	Bar graph	
Classification	Kurlov * (ratios) x	Vostroknutov * Durov * -triangular Hill * Piper *		Stiff o Rónai o (Tickell) *	Palmer-Rogers *	
Correlation	ratios x	Durov * -triangular	Schoeller x o Frey x o Rogers x o Cummulative x	Stiff o Rónai o (Tickell) *	Collins o * (Reistle) x	
Analysis	ratios x	(Hill) o Piper * Durov - doubled * Durov - tetrahedr. o —Simanovski vector graph * —	(Schoeller) x o Gráf *		Palmer *	
Synthesis	Number x (Kurlov) *		contour line x Maucha o	circular (diagrams) o Tickell x Stiff o Colby et al. o Rónai o	Collins o* (Reistle) x (Palmer-Rogers) *	color x shading xo hatching x

NOTE: underlined = predominant use
in bracket = inferior use

Values expressed in:
x milligrams per liter
o milliequivalents per liter
* percentage of milliquivalents per liter

Fig. 16. Summary of methods for representation of analyses.

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