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Abstract

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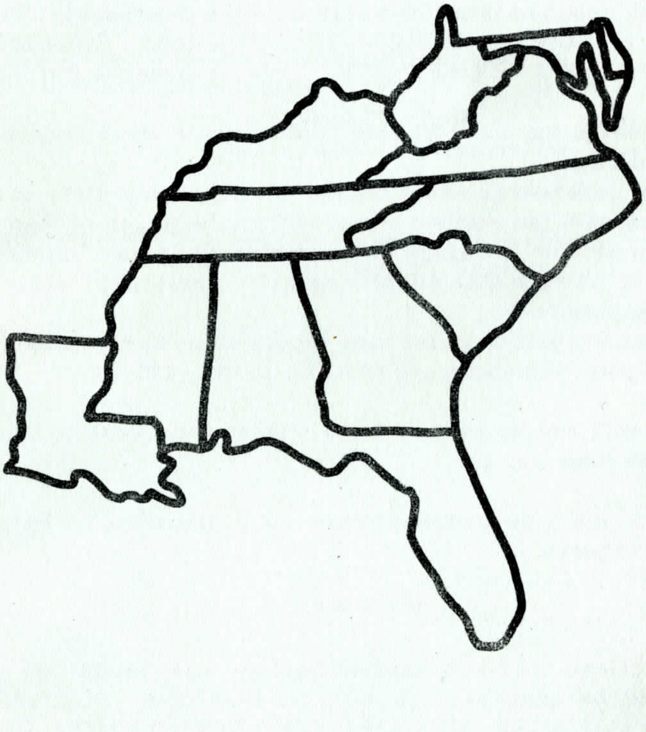
J. R. Butler

Southeastern Geology



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1962

DIGITAL COMPUTER PROGRAM FOR IDENTIFICATION OF MINERALS BY X-RAY DIFFRACTION

by

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ABSTRACT

The conventional x-ray diffraction method is limited in its application because the time required to make identifications from an x-ray pattern becomes excessive when a great many lines or peaks are present on a single pattern. This problem arises when a rock such as slate or shale is x-rayed without previous mineral separation.

Automatic data processing by Univac 1105 markedly reduces the time expenditure, provides a check on experimental errors, and eliminates errors caused by incorrect recording of d-spacing values from tables. A computer program has been developed which computes the d-spacings and makes an identification by picking out the d-spacings which characterize the mineral. Raw data for each sample include diffraction angles, peak or line intensities, and widths. When clay minerals are suspected, three x-rays are taken of each sample; randomly oriented untreated sample, randomly oriented heat-treated sample, and calcium-saturated glycerol-solvated oriented aggregate.

Test samples included sedimentary rocks for which the clay-mineral content had been determined by conventional methods and fine-grained metamorphic rocks of which petrographic thin sections and chemical analyses were available. The initial results on twenty-nine test samples have been promising. Almost all the major minerals or mineral groups were correctly identified by the computer method. The major disadvantage appears to be the failure to obtain positive identification on minerals present in small percentages. Many of the minor minerals can probably be identified from a randomly oriented sample of the heavy-mineral fraction of a rock. The present program is being expanded to include over 150 minerals.

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General Statement

Mineral identification by the x-ray diffraction method is based upon the d-spacing and intensity of three or more lines (for the powder photograph) or peaks (for the diffractometer chart) which are characteristic for a given mineral. The operator generally makes an identification by converting the diffraction angles to d-spacing values by use of Bragg's law and comparing the values with previously recorded lattice spacings for known minerals, or by direct comparison with x-ray patterns of known minerals. Complex mineral groups in which individual minerals give patterns that are closely similar to one another, such as the clay minerals and chlorites, require special treatment to distinguish the various members. For example, glycol solvation and heat treatment are used in the study of clay minerals. X-ray techniques have proven invaluable in the study of minerals which characteristically appear in cryptocrystalline or colloidal aggregates, the best example again being the clay minerals.

In many cases it is distinctly advantageous to study rocks without separating them into constituent minerals, because of the difficulties of mineral separation and because we would like to know which minerals coexist in a single rock. However, the multiplicity of the lines or peaks in the x-ray pattern of an aggregate of minerals makes the identification procedure much more time consuming and increases the chance of mis-identification or omission.

The purpose of this paper is to present the preliminary results of the application of automatic data processing to identification of minerals by x-ray diffraction. The raw data are diffraction angles taken from powder photographs or diffractometer charts, peak or line intensities, and widths. A digital computer determines the lattice spacing and makes an identification by picking out the characteristic lattice spacings for each mineral in the program.

At the very least, the program is useful because it computes the d-spacing for each diffraction angle, tabulates the data in a convenient manner, and decreases the chance of error in the computations. At best, it will be a rapid and accurate method for determination of the mineral composition of fine-grained aggregates of all types.

The senior author wrote the master program as a part of a course in automatic data processing in the Department of Mathematics, University of North Carolina. The program included the clay minerals and about 20 other common minerals in sedimentary rocks of the Atlantic Coastal Plain. The junior author became interested in the possibilities of applying the method to fine-grained metamorphic rocks such as many of the rocks of the Carolina slate belt. A supplementary program added some 55 other minerals and improved resolution of individual mineral species within solid solution series.

The ideal situation for petrologic studies would be to have complete information on mineral composition, bulk chemical composition, chemical composition of individual minerals, textural characteristics, and mineral orientation for each rock studied. As we approach this goal, the need for automatic data processing will become greater. Most geologists are not trained in the use of computers, but possibly could utilize computer techniques with knowledge of only the first stages of the process, i. e. setting up the problem and writing a flow sheet. Then a professional programmer could assist in translation into a computer language and in use of the computer. The writers believe that this approach is more realistic than attempting to learn the whole process of computer programming before using automatic data processing.

Acknowledgements

The writers wish to acknowledge the assistance of John W. Carr, III, who taught the senior author computer programming and numerical analysis and also assisted by providing computer time on the University of North Carolina Univac 1105. William Hanson and Patrick Cussick of the Computation Center of the University of North Carolina gave technical assistance. Frances S. Snipes and Gail S. Butler aided with drafting and typing. This research was supported in part by a grant from the University of North Carolina Research Council.

COMPUTER PROGRAM

Digital Computer and Language Used

The digital computer used was the Univac 1105, which is one of the larger and more complex computing machines. However, this program has been designed so that less elaborate machines can be used.

The computer language utilized was GAT (Generalized Algebraic Translator). This language was developed at the University of Michigan and is one of several languages currently used at the Computation Center of the University of North Carolina. It is a simple but powerful language and its simplicity makes it well suited to problems that confront the physical scientist. Although knowledge of such technical languages is useful, it is not necessary for the application of computer techniques, because professional programmers can be obtained for the language phase of computer programming. The scientist may not want to use more than two or three computer programs during his entire lifetime. Therefore, he may, with some justification, feel that the expenditure of time and effort required to master a language would more than offset the amount of time required to process his data by the use of the desk calculator, tables, etc. Problem analysis, flow charting, and analysis of results are more important to the scientist than the mechanics of computer languages. These three phases of programming are illustrated by each of the basic parts of this program: (1) Computation of d-spacings, (2) separation of k-alpha radiation from k-beta radiation, and (3) the mineral identification procedure.

Computation of D-Spacings

The computation of d-spacings was accomplished by repeatedly solving Bragg's equation:

$$\sin \Theta = \frac{n\lambda}{^{2}d}$$

Where:

Θ = the angle of diffraction in degrees

n = the order of diffraction (for our purpose $n = 1$)

λ = the wave length of the target material in the x-ray tube

d = the distance between atomic planes in angstrom units (d-spacing)

In order to solve this equation on a digital computer the equation is rewritten as follows:

$$\sin \left(\frac{2\theta_i}{2} \right) = \frac{\lambda_1}{2d_i}$$

$$d_i = \frac{\lambda_1}{2 \sin \left(\frac{2\theta_i}{2} \right)} .$$

Note that θ and d have been subscripted with the letter i and λ has been subscripted with the digit 1. The subscript, i, takes on the value 1, 2, ..., m, from the first to the last diffraction angle on the x-ray pattern. The symbol λ_1, stands for the wave length of Cu or Fe K-alpha radiation. Wave length (λ_2) is used for Cu or Fe K-beta radiation. The value of the angle of diffraction has been divided by two because the diffractometer and the powder camera used measure 2 θ, not θ. One more modification is made which depends on the subroutines for trigonometric functions used by the Univac 1105 at the University of North Carolina. These subroutines are in radian measure and are written

$$\theta \text{ degrees} = \frac{\theta}{57.296} \text{ radians.}$$

Substituting this relation we have

$$d_i = \frac{\lambda_1}{2 \sin \left(\dfrac{2\theta_i}{2 \times 57.296} \right)}$$

$$= \frac{\lambda_1}{2 \sin \left(\dfrac{2\theta_i}{114.592} \right)} .$$

Bragg's equation is now in the form required for a flow chart.

An explanation of the symbols used by the writers in flow charts is given in Figure 1. A list of variables and constants used in the flow charts is given in Table 1. The flow chart for computation of d-spacings (Figure 2) is a good illustration of flow-charting procedure. The "READ" statement means that all the input data are stored in the computing machine. Then proceeding in the direction indicated by the arrows the index or subscript i is set to one. Next, the variable x_1 is replaced by the quotient,

$$\lambda_1 \Big/ 2 \sin \left(\frac{2\ \theta_i}{114.592} \right) .$$

This equation is then solved until i equals m and the values of the X's are then typed out. The computing machine then proceeds to the next segment of the program.

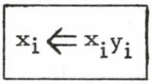
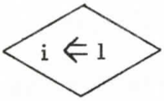
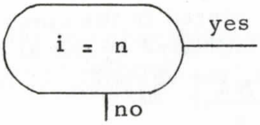
SYMBOL	MEANING OR USE OF SYMBOLS
$\Leftarrow$	"is replaced by"
	Control statements, such as start, halt, etc.
	Substitution or arithmetic expressions, for example, $x_i \Leftarrow x_i y_i$ This expression means that the value of x_i is replaced by the value of the product, $x_i y_i$. This symbol is also used for data input and output.
	Index setting, i. e., to set the initial value of an index or counter and to increment an index. Ex.: i is replaced by 1.
	Conditional statements. Ex.: Is i equal to n? All questions must be binary; yes or no.

Figure 1. Flow chart symbols

Table 1. List of variables used in the flow charts.

2θ = twice the angle of diffraction for K-alpha radiation, for glycerol solvated sample.

2ψ = twice the angle of diffraction for K-alpha radiation, for untreated sample.

2ρ = twice the angle of diffraction for K-alpha radiation, for heat treated sample.

λ_1 = wave length in angstrom units for Cu K-alpha (or other targets).

λ_2 = wave length in angstrom units for Cu K-beta (or other targets).

q = intensity of lines, glycerol solvated sample.

s = intensity of lines, untreated sample.

t = intensity of lines, heat treated sample.

u = width of lines, glycerol solvated sample.

v = width of lines, untreated sample.

w = width of lines, heat treated sample.

x = d-spacing in angstrom units, K-alpha radiation, glyc. solv.

y = d-spacing in angstrom units, K-alpha radiation, untreated.

Z = d-spacing in angstrom units, K-alpha radiation, heat treated.

a = d-spacing in angstrom units, K-beta radiation, glyc. solv.

b = d-spacing in angstrom units, K-beta radiation, untreated.

c = d-spacing in angstrom units, K-beta radiation, heat treated.

Separation of K-Alpha from K-Beta Radiation

Several kinds of radiation are emitted by an x-ray tube, but reflections of only one kind, k-alpha radiation, are used in identification of minerals. Reflections of k-beta radiation are rather common,

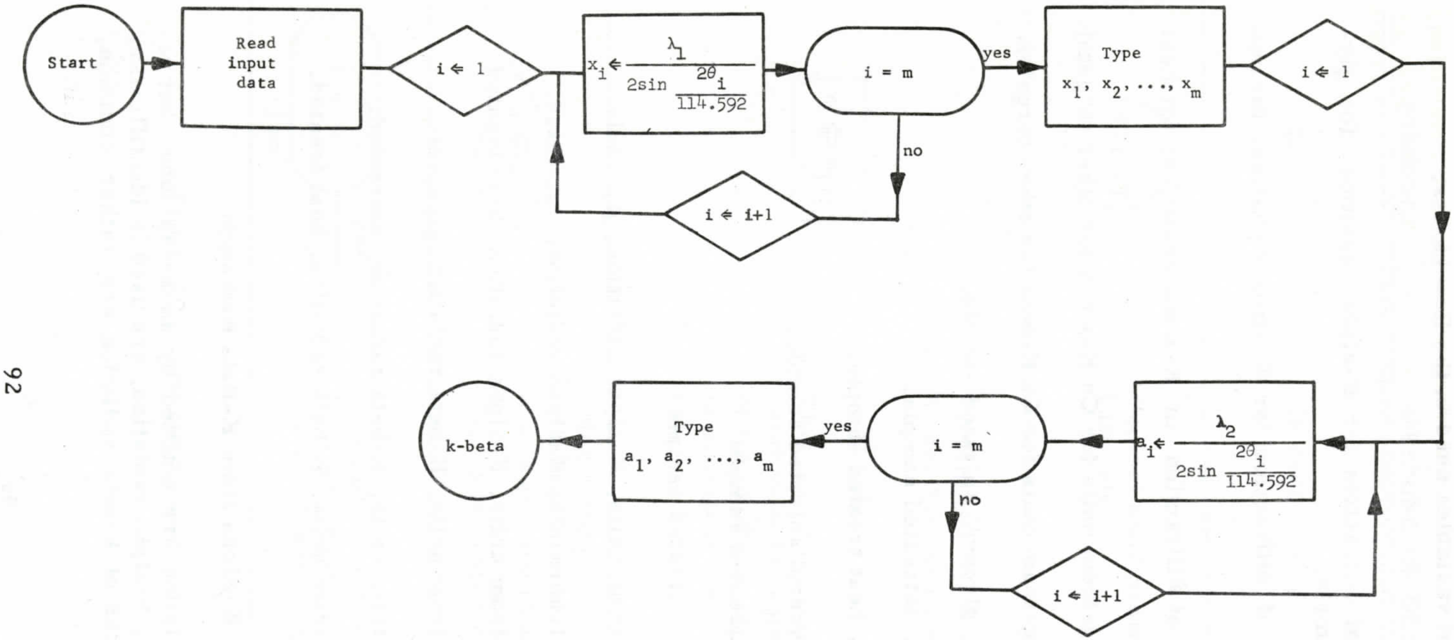


Figure 2. Flow chart for computation of d-spacings. Computations for x (glycerol-solvated sample) are illustrated here, those for y and z are similar.

therefore they must be distinguished from those of k-alpha radiation. In the program segment involving d-spacing computation, the spacings for k-beta radiation are also computed by replacing λ_1, the wave length for k-alpha radiation, by λ_2, the wave length for k-beta radiation.

After the d-spacings have been computed, the differentiation of k-alpha from k-beta radiation is accomplished as shown in Table 2 and Figure 3. The value of $d(\text{k-alpha})_2$ is compared with the value of $d(\text{k-beta})_1$ (Comparison One, Table 2). Then $d(\text{k-alpha})_3$ is compared with $d(\text{k-beta})_1$, $d(\text{k-alpha})_4$ is compared with $d(\text{k-beta})_1$, and so on; until $d(\text{k-alpha})_n$ is compared with $d(\text{k-beta})_1$. This procedure is repeated until $d(\text{k-alpha})_n$ is compared with $d(\text{k-beta})_{n-1}$. If any of these values are the same, for example, suppose $\left|d(\text{k-alpha})_3 - d(\text{k-beta})_2\right| < \epsilon$ (where ϵ = experimental error), and if the intensity of line 2 is less than the intensity of line 3, then the value of $d(\text{k-alpha})_2$ is cancelled because it is caused by k-beta radiation, not k-alpha radiation (Comparison Two, Table 2).

The cancellation procedure is accomplished by replacing $d(\text{k-alpha})_i$ by $d(\text{k-alpha})_{i+1}$ until $d(\text{k-alpha})_{n-1}$ is replaced by $d(\text{k-alpha})_n$. The value of $\underline{n}$ is then replaced by $\underline{n} - \underline{r}$ where $\underline{r}$ is a counter for the number of times that k-beta radiation only was responsible for diffraction lines or peaks.

Identification of Clay Minerals

The following sources of information were used in setting up the program: (1) the text by Brindley (1951), which is a standard reference for clay mineral studies; (2) a recent paper by Warshaw and Roy (1961), which is an excellent summary of identification procedures for layer silicates; (3) notes from courses in x-ray techniques taught by R. L. Ingram at the University of North Carolina; and (4) the X-ray Powder Data File of the American Society for Testing Materials.

The clay minerals are divided into three main groups on the basis of first-order basal spacings: 14-angstrom, 10-angstrom, and 7-angstrom groups. Since the lattice spacings of some clay minerals vary with the state of hydration, special treatment of samples will aid in identification of the clay minerals. Therefore, three x-rays are taken of each sample: (1) untreated (not oriented), (2) heat treated (not oriented), and (3) glycerol solvated (oriented). Basal spacings for montmorillonite, chlorite, endellite, and kaolinite illustrate the value of heat treatment and glycerol solvation in identifying clay minerals (Table 3).

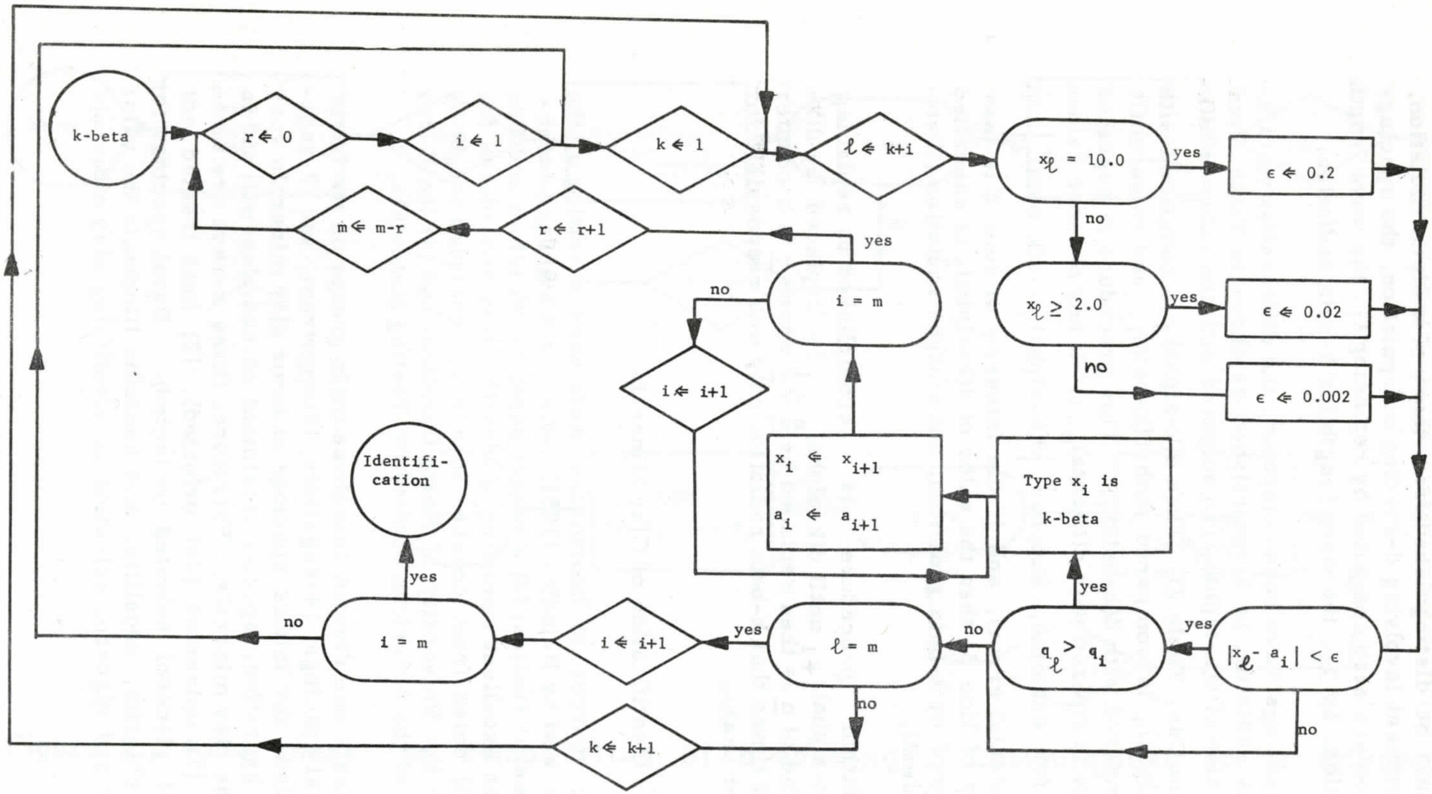


Figure 3. Flow chart for detection and cancellation of k-beta radiation. Computations for y and z are similar.

Table 2. Procedure used in detection and cancellation of K-beta radiation.

COMPARISON ONE

Number	1	2	3 ... n-2		n-1	n
d(K-alpha)	7.10	4.93	3.57	2.48	1.83	1.63
d (K-beta)	6.37	3.57	2.81	2.11	1.79	1.42

(No cancellations, therefore cancellation counter, r, = 0)

COMPARISON TWO

Number	1	2	3 ... n-2		n-1	n
d (K-alpha)	7.10	~~4.93~~	3.57	2.48	1.83	1.63
d (K-beta)	6.37	3.57	2.81	2.11	1.79	1.42

(Cancellation, therefore cancellation counter, r, = 1.)

CANCELLATION ONE

Number	1	2	3 .....n-2	n-1
d (k-alpha)	7.10	3.57 (value of n-pth term)	1.83	1.63
d (K-beta)	6.37	2.81 (value of n-pth term)	1.79	1.42

Note: Comparison and cancellation procedure repeated until the n-rth term is compared with the n-(r+1)th term.
The value of n then becomes n-r.

Table 3. Response of some clay minerals to heat treatment and glycerol solvation.

Mineral	Treatment				
	Glycerol solvation	Untreated	Heat		
				Time	Temp.
Montmorillonite	18 A	14 A	10 A	12-15 hrs.	250°C.
Chlorite	14 A	14 A	14 A*	1 hr.	550°C.
Endellite	10-11 A	10-11 A	7 A	8 hrs.	110°C.
Kaolinite	7 A	7 A	**	1 hr.	550°C.

* intensity increases
** disappears

In the computer program, the variables x, y, and z are assigned to the d-spacings of the glycerol solvated, untreated, and heat treated portions of the samples, respectively. The use of these three variables can be illustrated by the test for the presence of montomorillonite from the flow chart for clay mineral identification (Figure 4). First the variable y is tested to determine whether or not the 14-angstrom line is present. If so, the variable x is examined to determine whether or not the 14-angstrom line has expanded to 18 angstroms. If the 18-angstrom spacing is present, the variable z is tested to see if the 14-angstrom line has collapsed to 10 angstroms. If all these conditions are met, the mineral is identified as a montmorillonite and then subdivisions are made. In general, the same scheme of comparison of the variables x, y, and z is followed for all the clay mineral groups. Subdivisions of the 14-angstrom, 10-angstrom, and 7-angstrom groups depend primarily upon diagnostic d-spacings, other than the basal spacings, from the untreated portion.

Identification of Non-clay Minerals

The non-clay minerals are identified by a line-by-line check of d-spacings obtained from an untreated, randomly oriented portion of the rock sample. The flow chart for this procedure is shown in Figure 8. D-spacings for three or more of the most intense and/or diagnostic lines or peaks of a mineral are stored in the program, and a positive identification is made if they are present in data from the sample. The

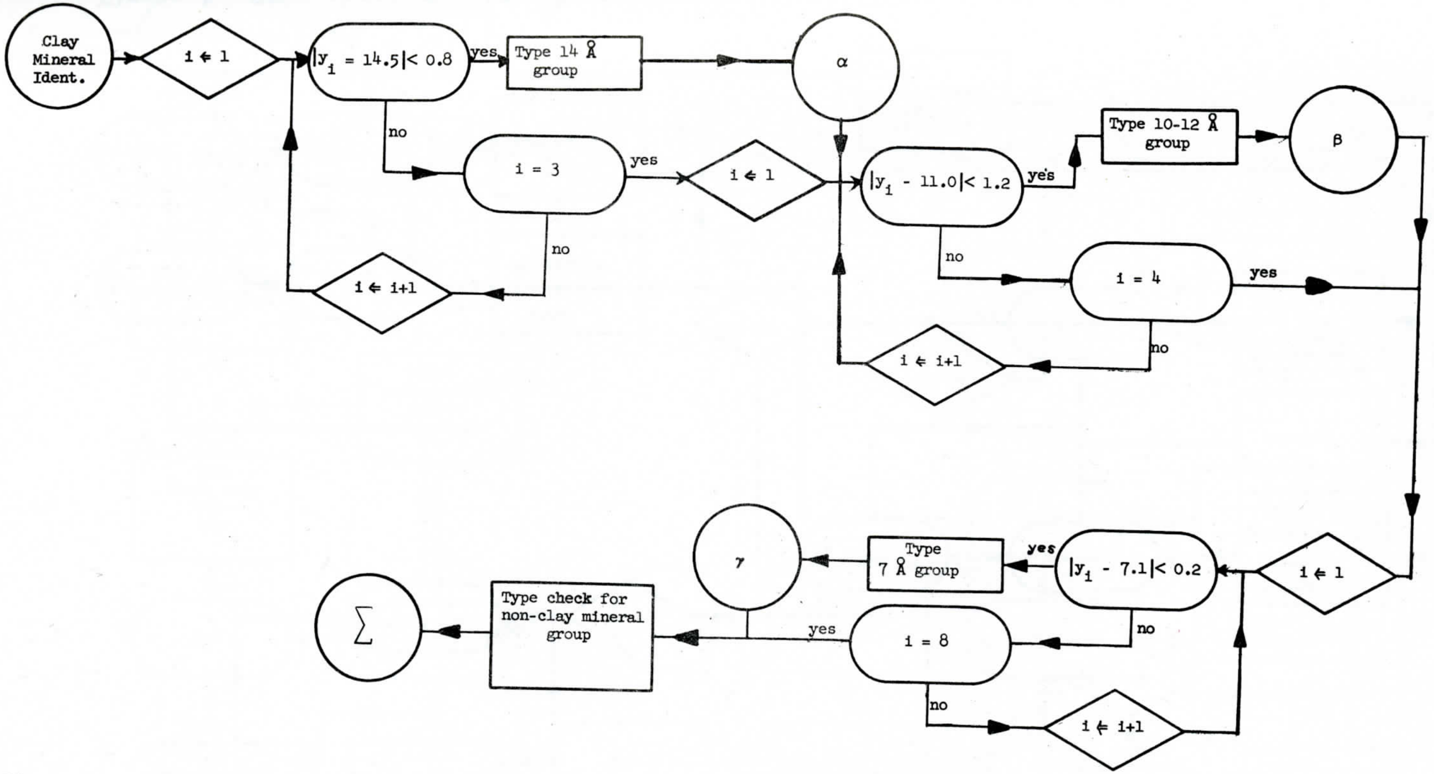


Figure 4. Flow chart for identification of clay minerals.

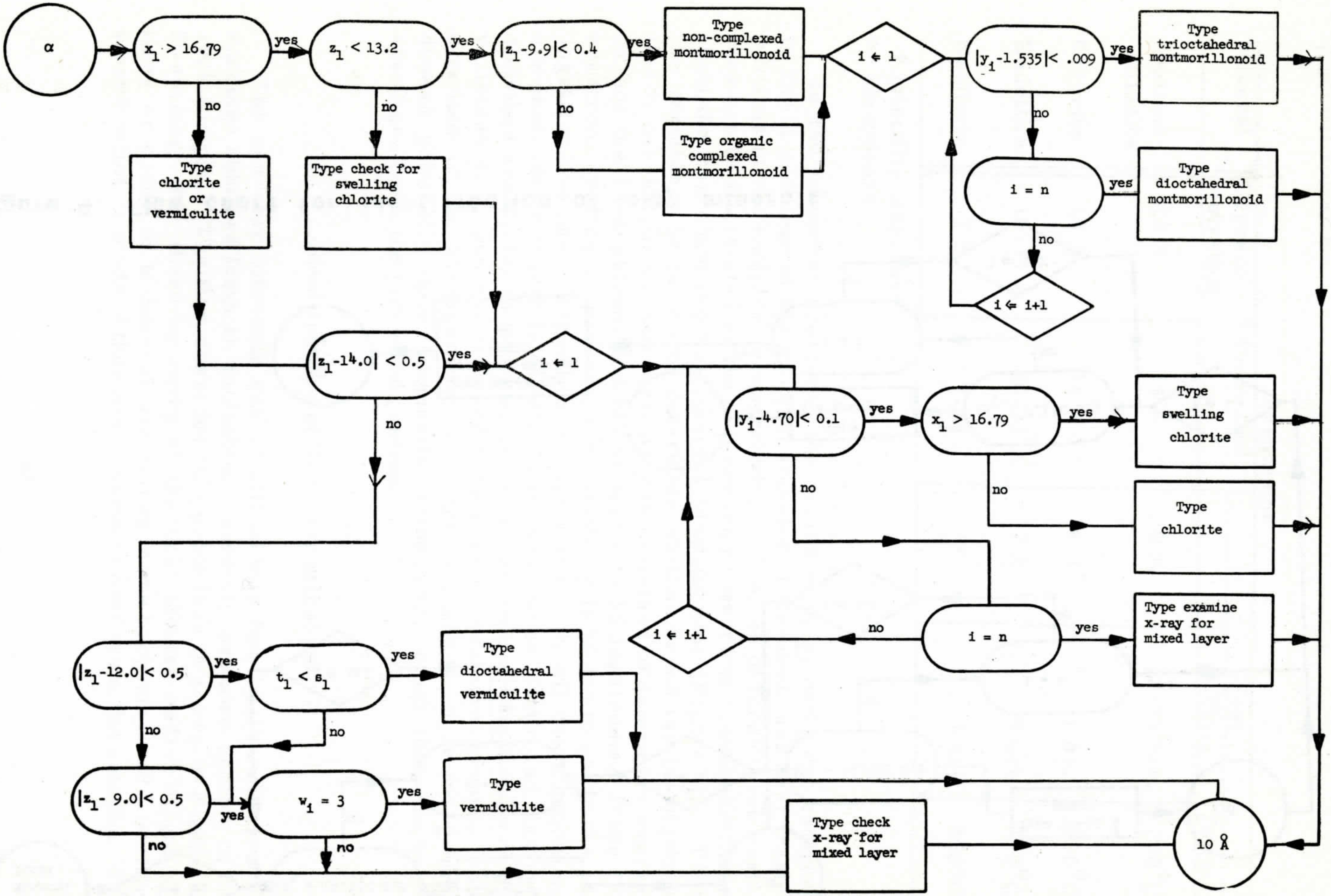


Figure 5. Flow chart for 14 angstrom group.

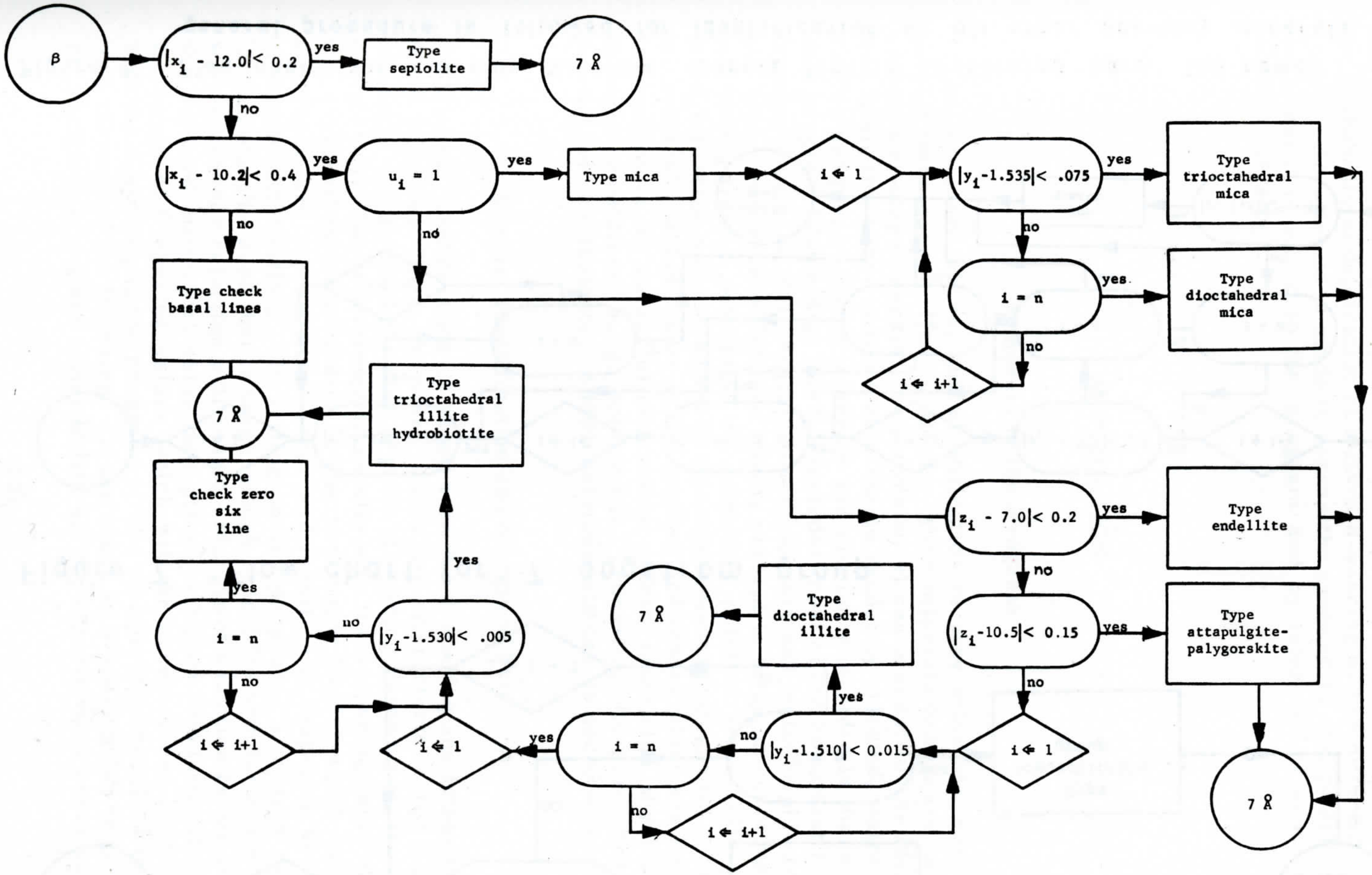


Figure 6. Flow chart for 10-12 angstrom group.

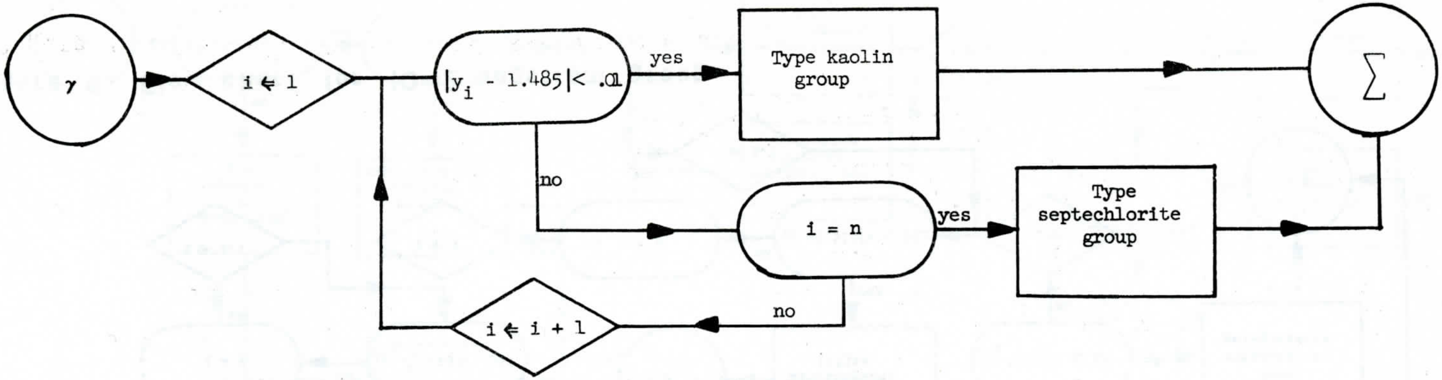


Figure 7. Flow chart for 7 angstrom group.

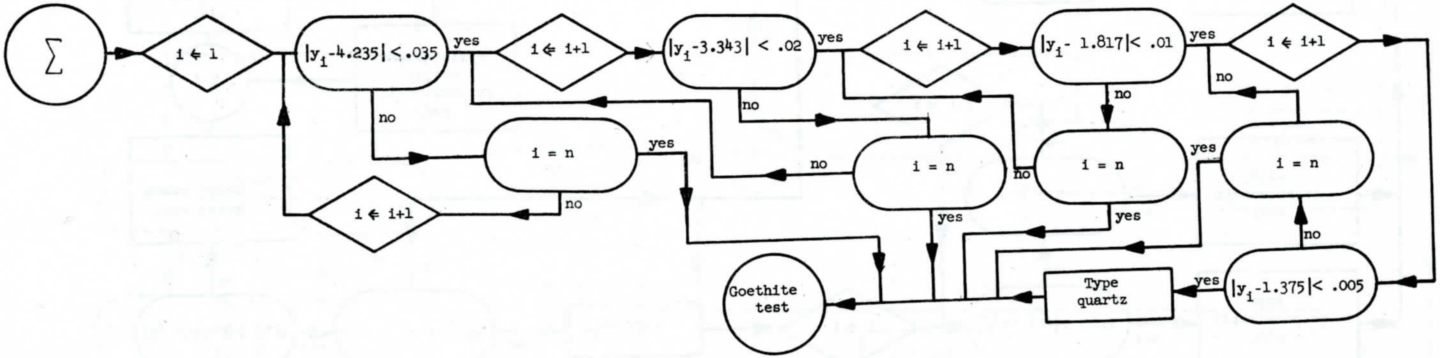


Figure 8. Flow chart for non-clay minerals. Quartz test is illustrated here. The same general procedure is followed for identification of all other non-clay minerals.

number of d-spacings required for positive identification depends upon the probability of duplication of a given d-spacing by two different minerals. An attempt is made to assess the probability of duplication as the mineral is added to the program and by later use of samples of known mineralogy.

APPLICATION

Minerals in the Program

As discussed above, the identification of clay minerals requires special techniques. Nearly all the other minerals (which are herein called "non-clay minerals" for convenience) can presumably be identified from the x-ray pattern of a single randomly oriented, untreated powder sample. Eighty minerals are presently included in the computer program (Table 4). The list includes most of the important rock-forming minerals of fine-grained sedimentary and metamorphic rocks and other minerals which are rarely present in large amounts but are interesting from a petrologic or economic point of view. Over 70 more minerals will be added to the supplementary program. These minerals will include some of the zeolites and others which are limited in occurrence to rocks formed under rather restricted physical or chemical conditions; e. g. spodumene, grunerite, diaspore, brucite, jadeite, and smithsonite. Additional minerals can be added as needed.

Mineral Identification and Margin of Selection

Mineral identification is based upon the d-spacing and intensity for three or more lines or peaks which are characteristic for a given mineral. It is unlikely that a given d-spacing determined from the sample will always correspond exactly with the d-spacing value of the same mineral in the program. The two major factors which cause a difference are experimental error and variation in d-spacing because of atomic substitution. In setting up the program, a margin of selection must be used that is large enough to include both factors, otherwise erroneous rejection will result. Margin of selection is defined as the selected numerical value that places a higher and lower limit on the range of d-spacing values which will be accepted and correlated with the d-spacing in the program. The margin of selection is therefore the sum of the following: (1) the range in d-spacing due to chemical variation in a given mineral, and (2) the experimental error caused

Table 4. List of Minerals in the Program

- I ELEMENTS
  - Gold
  - Graphite
- II HALIDES
  - Fluorite
  - Ceragyrite
- III SULFIDES
  - Pyrite
  - Calaverite
  - Cooperite
- IV OXIDES AND HYDROXIDES
  - Magnetite
  - Ilmenite
  - Hematite
  - Goethite
  - Gibbsite
  - Rutile
  - Corundum
  - Anatase
  - Brookite
  - Cassiterite
  - Chromite
  - Spinel group, with subdivisions
- V CARBONATES
  - Calcite
  - Dolomite
  - Siderite
  - Rhodocrosite
- VI SULFATES, PHOSPHATES, ETC.
  - Gypsum
  - Anhydrite
  - Apatite
  - Scheelite
  - Barite
  - Wolframite
  - Xenotime
- VII SILICATES
  - 1. Tektosilicates
    - Silica group
      - Quartz
      - Cristobalite
    - Feldspar group
      - Orthoclase
      - Plagioclase
    - Dumortierite
  - 2. Phyllosilicates
    - Talc
    - Pyrophyllite
    - Ortho-serpentine
    - Steatite (Talc 2)
    - Glauconite
    - Chlorite group
      - Septechlorite
      - Diabantite
      - Penninite
      - Sheridanite
    - Micas
      - Vermiculite
      - Muscovite
      - Biotite
      - Phlogopite
    - Clay minerals
      - Montmorillonite, with subdivisions
      - Swelling chlorite
      - Illite, with subdivisions
      - Sepiolite
      - Halloysite (endellite)
      - Nacrite
      - Dickite
      - Kaolinite
      - Attapulgite - palygorskite
  - 3. Inosilicates
    - Actinolite - tremolite
    - Anthophyllite
    - Hornblende
    - Diopside
    - Augite
    - Enstatite
    - Hypersthene
  - 4. Cyclosilicates
    - Tourmaline
    - Cordierite
    - Rhodonite
    - Beryl
  - 5. Sorosilicates
    - Epidote group
  - 6. Nesosilicates
    - Sphene
    - Zircon
    - Chloritoid
    - Topaz
    - Olivine group
      - Forsterite
      - Fayalite
    - Sillimanite (aluminosilicate) group
      - Kyanite
      - Sillimanite
      - Andalusite
    - Garnet group
      - Almandine
      - Spessartite

mainly by small inaccuracies of measurement of the angle of diffraction.

If several different values are given in different sources for d-spacing of the same lattice plane of a mineral, a margin of selection is chosen so that none of these values would be rejected. For example, one d-spacing of quartz is listed as 4.21 by Brindley (1951), 4.25 by Berry and Thompson (1962), and 4.26 by ASTM card no. 5-0490. Table 5 shows that the estimated experimental error in this range is 0.01 angstrom units. Therefore, the value used in the program would be 4.235 ± 0.035. The figure 0.035 is the margin of selection.

Choice of margin of selection is subject to human error because it partly depends upon experience of the programmer and reliability of data for any given mineral. If there is overlap of the margins of selection for d-spacings of two or more minerals, then the chances of erroneous identification are increased. Therefore, it is advisable to keep the margin of selection as small as possible.

The computer scans the data for each sample and chooses those d-spacings which fall within the margin of selection. Three or more d-spacings are considered necessary for positive identification. On the output data sheet, the appropriate d-spacings, if any, are tabulated for each mineral. Therefore, the operator can see at a glance how many d-spacings were used in the identification of a mineral and the values are readily available for further checking, if necessary. A typical data sheet will list no d-spacings for most of the minerals, one or two for several minerals, and three or more for the major minerals. The number of minerals positively identified in the test samples was rarely less than three or more than six.

Test Samples

In order to test the accuracy and efficiency of the computer identifications, two groups of samples were run: (1) Seventeen sedimentary rocks, containing clay minerals for which identifications were made by an experienced operator using the conventional methods. (2) Twelve low-rank metamorphic rocks, for which thin sections were available and identifications could be checked by optical means. For both groups, results were very good. Almost without exception, the major minerals were correctly identified by the computer method. However, minerals that make up less than about ten per cent of the rock rarely are positively identified, and generally d-spacing values are absent for minerals that make up less than three or four per cent. The identification problem of minor minerals is not primarily a fault of the

Table 5. Experimental error and margin of selection.

Estimated experimental error (in angstrom units)

d-spacing	error
>10	0.1
10-2	0.01
<2	0.001

Typical margins of selection (in angstrom units)

d-spacing	margin of selection
> 12	±0.8
10-12	0.5
7-10	0.2
6-7	0.1
5-6	0.05
4.5-5	0.04
3.5-4.5	0.03
2-3.5	0.02
<2	0.01

computer method, but results from the use of rock samples without previous mineral separation. Special techniques will probably be necessary to improve the results for minor minerals.

To illustrate the problems and limitations of the computer method, results for several of the samples will be discussed. For the sedimentary rocks (Table 6), mineral identifications by both methods are in agreement, except that gibbsite in Example 4 was not identified by the computer method. One diagnostic line, which was present on the pattern from the oriented aggregate, was absent from the pattern of the untreated sample. Since the line-by-line check by the computer is made only on data from the untreated sample, gibbsite was not identified by the computer method.

Most of the low-rank metamorphic rocks used for test samples are slates and phyllites from the Carolina slate belt, and are metamorphosed argillites, tuffs, and lava flows. Thin sections were used for identification of minerals and estimation of percentages. Chemical analyses are available for four of the samples.

In the first example (Table 7), only the two major minerals were identified. Several mica spacings were present, but positive identification was not made because of absence of the 10-angstrom spacing. Small amounts of a mineral with high relief were observed in thin section and tentatively identified as sphene or rutile. The computer data sheet listed two spacings for rutile, two for anatase, and none for sphene or zircon. A manual check showed that other spacings were present for anatase, a mineral with somewhat similar optical properties as sphene and zircon.

In Example 2, identifications are the same for the major minerals. Calcite spacings were present, but not enough for positive identifications. Feldspar group was tentatively identified on the data sheet; this group is difficult to distinguish from quartz in grains too fine for optical determinations. Correspondence is good for identifications in Example 3, except that no spacings were listed for chloritoid, which is present in significant amounts. The data for Example 4 show that actinolite and "leucoxene" were not identified by x-ray, and the data sheet lists a 7-angstrom mineral which was not distinguished by microscope.

PROBLEMS OF APPLICATION

Duplication of D-Spacing Values

A possible source of error is mis-identification because of duplication of lines. A mineral may be listed as present if values for some of its characteristic d-spacings are approximately the same as those values for one or more other minerals. The possibility of duplication depends largely upon the number of d-spacings used in identification of each mineral, the magnitude of the margin of selection set up for each d-spacing value, and the number of minerals in the sample.

For those minerals that are likely to be confused with one another, more d-spacing values can be used in the program. A smaller value for the margin of selection may decrease the chances of duplication, but it increases the possibility of erroneous rejection of values.

On the basis of first results, duplication of values does not appear to be a serious problem. In a few cases identification of an "exotic" mineral appeared in the data sheet, but manual checking of d-spacing values showed that it was not present. Sphene was identified in one sample on the basis of three d-spacings, but a manual check disclosed that the d-spacings were from three other minerals. Therefore,

Table 6. Results for four sedimentary rocks.

Formation and sample number	Lithology	Mineral Identification	
		Computer method	Conventional method
1. Barnwell(?) No. 71/E	argillite	Trioctahedral montmorillonite Muscovite Kaolinite Quartz	Trioctahedral montmorillonite Muscovite Kaolinite Quartz
2. Tuscaloosa, No. 47/1.	clay	Kaolinite Quartz	Kaolinite Quartz
3. Tuscaloosa, No. 73/1.	sand, argillaceous, micaceous	Muscovite Kaolinite Quartz	Muscovite Kaolinite Quartz
4. Barnwell No. 74/3	shale, purple	Chlorite, var. sheridanite (?) 10 A group Kaolinite - - - Quartz Hematite	Chlorite, var. sheridanite (?) 10 A group Kaolinite Gibbsite Quartz Hematite

sphene is likely to be erroneously identified in any mixture containing these three minerals. The results must constantly be checked to prevent errors of this type.

Many of the duplication errors can probably be anticipated and eliminated by careful selection of the values that are written into the program. For example, if a mineral has one or more lattice spacings that correspond to those of quartz or another common mineral, the program can be set up to use additional d-spacings or values that are less likely to be duplicated. Minerals with a pronounced chemical variation, such as the garnets or chlorites, present a somewhat dif-

Table 7. Results for four low-rank metamorphic rocks.

Sample	Computer identification	Miscroscopic identification and estimated percentages *	
1. Chlorite phyllite, No. SC-3, Newberry County, S. C.	chlorite, var. sheridanite(?)	chlorite	44%
	quartz	quartz	43
		sericite	12
		sphene or rutile	1
2. Sericite phyllite, No. OC-19A, Orange Co., N. C.	chlorite, var. sheridanite(?)	Chlorite	60
	muscovite	sericite	
	quartz	quartz	36
	feldspar(?)		
		calcite	trace
		opaques	4
3. Pyrophyllite-hematite phyllite, No. NC-24B, Moore Co., N. C.	quartz	quartz	56
	pyrophyllite	pyrophyllite	24
	hematite	hematite	11
		chloritoid	9
4. Greenstone, No. OC-28C, Orange Co., N. C.	chlorite, var. sheridanite(?)	chlorite	28
	muscovite	sericite	16
	7-angstrom group		
	quartz	quartz	10
	epidote	epidote	35
	plagioclase		
		actinolite	7
		"leucoxene"	4

*Percentages given are visual estimates only.

ferent problem. All the minerals of the group give the same general pattern, with variations in lattice spacings caused by atomic substitution. In the original program, no varieties of the orthochlorite group were included. The supplementary program subdivides the orthochlorites into three varieties: diabantite, penninite, and sheridanite. Further revision is being attempted. Initial results appear to be good, but should be verified on samples of known minerals. Detailed analysis of sources of error in all stages is needed.

Minerals Present in Small Percentages

In the x-ray pattern of a mineral aggregate, lattice reflections from the minor minerals may not appear. Minerals that make up less than five or ten per cent of the rock may not be represented by any d-spacings or there may be too few for positive identification. These minor minerals may be of considerable petrologic significance. For example, chloritoid, which is a valuable index mineral of low metamorphic grade, was not identified in a sample of phyllite from the Carolina slate belt because it made up only nine per cent of the rock and because Cu radiation was used. Use of an x-ray tube with Fe target would probably improve results for the iron-bearing minerals.

This problem has no easy solution. An x-ray pattern (using Fe radiation) of the heavy mineral fraction would yield much information on the minor minerals, but nearly doubles the amount of time spent on each sample. This approach is under study at the present time.

Minerals with Pronounced Chemical Variation

The pronounced chemical variation in some mineral groups causes a variation in d-spacings which may make the process of identification more difficult. For example, there is continuous solid solution between the end members of the olivine group, forsterite and fayalite. Representative d-spacings of the end members illustrate the wide variation:

	d_{130}	d_{131}	d_{112}
Synthetic forsterite	2.766	2.510	2.456
Synthetic fayalite	2.829	2.565	2.500

(Values from Yoder and Sahama, 1957)

If only the end members are included in the program and the margin of selection is ± 0.02 Angstrom units, then an intermediate member of the series might have d-spacing values which would be rejected and the mineral would not be identified. This problem necessitates careful selection of values to cover the entire compositional range. For some mineral groups, the needed information is not yet available. Therefore, the program will need revision as new data are obtained.

If chemical variation causes very little variation in d-spacings, as in the plagioclase feldspars, the individual mineral species may be difficult to distinguish. In the present program, the margin of selection for plagioclase and other groups that present similar problems is set up to include the whole group and an attempt is made to distinguish minerals within the group by manual check.

Future Research

A program of testing is being set up, using artificial mixtures of known minerals in various proportions. Such testing should provide a better check on accuracy, reliability, and the lower limit of identification than the rock samples in this report.

In the rocks presently being studied, the major minerals are most commonly quartz, feldspars, and the Phyllosilicates; nearly all of these minerals have specific gravity less than 2.85. The accessory and minor minerals are generally Oxides, Sulfides, and Nesosilicates, which are almost invariably heavier than 2.85. Therefore, heavy mineral fractions are being separated by use of bromoform (S.G. 2.85) for identification of minerals present in small percentages. This method shows promise, but adds to the time required to process each rock. Some minor constituents may still be overlooked if they are removed with the light fraction (e.g. zeolites, scapolite, cordierite, gypsum, calcite, beryl, graphite).

No attempt has yet been made to determine percentages of minerals present. If standards were set up for a limited suite of rocks, peak-height or line-intensity analysis theoretically would yield semiquantitative information on mineral percentages. Standards are currently being set up for a suite of slates and phyllites from the Carolina slate belt, using modes determined by the point-count method.

It will probably be necessary to add more minerals to the program and to revise the data for some minerals as new information becomes available. A number of relatively rare rock-forming minerals have been omitted from the program: feldspathoids, melilites, monticellite, larnite, telleyite, rankinite, spurrite, nahcolite, natron, trona, soda niter, the borate minerals, and others.

Conclusion

We believe that the feasibility of automatic data processing in the study of cryptocrystalline and fine-grained microcrystalline mineral aggregates has been demonstrated by the preliminary results of this study. Application of the method to petrology of low-rank metamorphic rocks appears particularly promising. Very little is known about the mineralogical changes that take place in the advanced stages of diagenesis and the beginnings of metamorphism. The method may also be useful in studies of heavy mineral suites, hydrothermal alteration, and weathering.

Obviously, rigorous error analysis and further testing with known samples are needed. More than 70 more minerals will be added to the program and the data for some of the original minerals will be revised. Further revision will be necessary as new data become available.

The major advantages and disadvantages are as follows:

Disadvantages:

1. Minerals of low percentage are rarely identified. This is a limitation of the x-ray technique rather than automatic data processing, and may be partially overcome by using an x-ray of the heavy mineral residue in addition to x-rays of the unseparated aggregate.

2. Mis-identification or omission may result from erroneous or inadequate original data, improper margin of selection, and duplication of d-spacings.

Advantages:

1. The d-spacing is computed for each diffraction angle. In the conventional method, tables or charts are used to convert the diffraction angle to d-spacing, and mistakes in reading or interpolation are possible. Diffraction angles can be read to two decimal places on diffractograms of some modern x-ray equipment, but the tables are set up for values to only one decimal place. Thus the computer method takes advantage of the increased accuracy of modern equipment in computing d-spacings.

2. K-beta radiation is detected. This is necessary because some k-beta radiation will appear on the x-ray pattern even though filters are used. In fact, if filters were used that were sufficiently thick to filter out all k-beta radiation, weak k-alpha radiation would also be filtered out.

3. The major advantage is that the time-consuming process of conventional line-by-line checking is done automatically. The computer always checks for every mineral in the program, but such a thorough check is not feasible for a human.

4. The output data are tabulated in a convenient form so that both positive and tentative identifications can easily be checked, if desired.

5. Many mistakes are avoided, since the computer handles the routine computations.

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GEOMORPHOLOGY AND THE SEDIMENT TRANSPORT SYSTEM

by

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ABSTRACT

The sediment transport system consists of source, gradient, and sink. The prime factors governing the operation of this system are materials, energy (process) and environment ("climate"). Over a period of time, these factors operate in such a manner that an equilibrium form is produced. Such an equilibrium form, once established, must be independent of time, as long as the controlling factors are held constant. This observation is clearly opposed to one of the fundamental principles of the Davis scheme which stated that form *is* time-dependent.

Materials have various important properties, including resistance to certain processes (such as weathering); areal variability; and directional variability (aelotropic weathering). These properties, in conjunction with energy (process) and climate, determine the equilibrium form.

Potential, or available, relief is an indicator of the nature of the energy gradient. The latter cannot be taken as a pure gravity gradient, however, because other forms of energy (wind; waves) are also important. In some areas, such as along the beach, gravity may plan a relatively minor role in fixing the gradient. Contour lines, therefore, are not necessarily isopotential lines.

INTRODUCTION

The sediment transport system consists of source, gradient, and sink.* The geomorphologist, the sedimentologist, the stratigrapher, and the structural geologist must think in terms of these components. The prime factors in the development of this system are materials (provenance), energy (process), and environment (climate).

The concept of materials includes (a) rock type and its weatherability, (b) areal variability, and (c) rock aelotropism (directional variability of weathering). The first of these aspects might contrast clay and granite; under certain conditions, one weathers readily, the other not so readily. The second has to do with areal variability, and is closely related to the stratigrapher's concept of facies. Rock units generally differ in lithologic character from place to place. For this reason, a single unit may weather readily in one area, not so readily in another. Moreover, fracture patterns, which also influence weathering, vary areally. The third of these aspects distinguishes between isotropic rocks, which weather equally rapidly in all directions, and aelotropic rocks, which have preferred weathering directions. Examples of the latter can be seen in mesas, buttes, cuestas, and hogbacks, which maintain their distinctive forms because weathering proceeds more easily parallel with the bedding than normal to it. Where aelotropic rocks are present, structural attitude must be specified.

The energy concept used here is not total energy, but mechanical or physical energy expended in the transport of the products of weathering. Potential relief (available relief) provides, in many cases, an approximation to potential energy. This is only an approximation, however, inasmuch as gravity is not the only component of the energy gradient (for example, wind energy and wave energy are also important in the movement of detritus). The kind, level, and variability of the energy need to be determined.

ENVIRONMENT

Environment is a complex of many physical, chemical, and bio-

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*The term "sink" has been widely used to refer to a funnel-like depression eroded (by solution) in limestone or other soluble rocks. It is not so used in this discussion. The concepts of source, gradient, and sink are so well entrenched in potential theory, and in those sciences which are in part based thereon, that the present writer feels they should not be abandoned, even though slight confusion may arise from their continued use. In fact, major future developments in the study of the sediment transport system will probably have to be undertaken in terms of potential theory; therefore, the source-gradient sink terminology may as well be adopted now.

logical factors, not all of which are understood singly, much less in combination. In the source area, environment may be represented by climate, which in turn can be subdivided into four types of primary interest to the geologist: wet, hot dry, cold dry, and temperate (Tanner, 1961). This simple scheme is based on the fact that very few low-rainfall areas have moderate potential evaporation rates (hence hot dry and cold dry are easily separable), and very few high-rainfall areas have either very low or very high potential evaporation rates (hence there is only "wet", rather than hot wet and cold wet). On a plot of total precipitation versus potential evaporation, the four classes stand out reasonably clearly. They can be limited approximately as follows:

1. Wet. Total precipitation exceeds about 120 inches annually.
2. Hot dry. Precipitation is less than about 10 inches, and potential evaporation more than about 70 inches, annually.
3. Cold dry. Precipitation and potential evaporation are less than about 10 inches, each, annually.
4. Moderate. Precipitation is between about 10 and 120 inches, and potential evaporation is between about 10 and 70 inches, annually. This class includes distinctive sub-classes: notably where precipitation and potential evaporation are roughly equal, at about 50 to 100 inches per year, and highly seasonal (savanna climate); and where precipitation is less than about 20 inches per year (semi-arid and steppe climates).

More detailed climate studies have not proven particularly useful for the geologist, although valuable for the climatologist (Trewartha, 1954). Peltier (1950) has constructed a morphogenetic climate scheme based on rainfall and temperature data, but the classes therein are not as easily distinguishable as those given above.

Environment also affects the gradient, but its importance here is thought to be greatly diminished. In the sink, or depositional area, environment is, commonly, a matter of soil or oceanographic conditions, which in turn may be related to climate.

EQUILIBRIUM

Over a period of time, rocks exposed to weathering at any given place will develop an equilibrium form which represents a mutual adjustment among the three basic factors (materials, energy, environment). As long as these three factors are held constant, the same equilibrium form will continue to exist, although its position may be altered (for example, moved closer to sea level or to some other base level).

This conclusion is clearly opposed to the Davis notion of time-dedendent development (that is, that the geometry of the land form depends primarily on the length, or duration, of weathering), with its corollary system of young, mature, and old regions.

The equilibrium idea was essentially covered in the German concept of "stockwerk" (von Engeln, 1942), which dates from several decades back. According to the stockwerk idea, a specific, persistent equilibrium form is determined by certain energy-rock relationships (Figure 1). Mackin (1948) applied the equilibrium concept to rivers, Tanner (1958) extended it to beaches, and Hack (1960) has restated it in a more general form. Equilibrium is not a short-term condition, as these writers have been careful to point out.

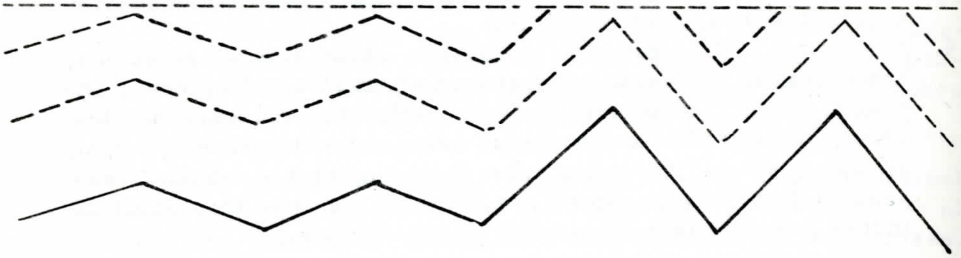

Figure 1. Simplified diagram showing the basic idea underlying the stockwerk concept. The horizontal dashed line represents an erosion surface which has been dissected. The rocks underlying the region to the right differ from those underlying the region to the left. As a result, different hillside slopes are established in the two regions. Modern hilltops (peaks on solid line) occur at two different levels. These levels reflect a single history, rather than two "old peneplanes". This idea is specifically based on the notion of the equilibrium form.

Adoption of the equilibrium concept does not completely destroy the Davis cycle of youth, maturity, and old age. If there is an equilibrium state, then there must be a sub-equilibrium state, which exists until equilibrium conditions have been realized. These two states compare in some ways at least, with the Davis ideas of youth and maturity. It is difficult to conceive of a "super-equilibrium" condition. It is more likely that the "old age" designation really pertains to an area where the basic conditions of equilibrium have been altered, perhaps because the amount of potential (or available) relief has been greatly reduced. The latter might be achieved in an area where, for example there was no longer any active orogeny or uplift.

Equilibrium represents a dynamic (and therefore shifting) balance among materials, energy, and environment. Our present understanding of the geologic past suggests that, broadly speaking, energy has been more variable than the other two. A region may pass, tectonically, from long-term stability, to great mobility, and then gradually back to stability. If the period of activity includes appreciable uplift, then ground-level climates will be changed exclusively as a result of this fact. The equilibrium form developed on any single rock type may well be distinctive for each of at least four periods: early stability, rapid uplift, gradual deceleration of tectonism, and late stability. It is also probably that the period of late stability will include two subperiods: one when potential relief if still high, and another, much later in the history of the region, when potential relief is approaching a minimum. This is, of course, an overly simple picture, having only a single sharp orogeny, whereas in nature many successive pulsations may take place.

Penck (1924) conceived of an equilibrium form which was also slightly skewed (that is, either more uplands than lowlands, or vice versa) depending on whether uplift or downcutting were more active at the moment. He conceived of the alternation between "uplift" and "down-cutting" as operating something like a see-saw, with first one slightly ahead, and then the other. There was no cycle, only a zig-zag line. In the Penck system, steepening slopes indicated tectonic activity, and reclining slopes could be interpreted as due to erosion.

Davis (1954) adopted, for convenience, the notion of a single, sharp uplift, followed by a long period of still-stand during which the processes of erosion reduced the uplifted area. His notion of youth, maturity, and old age can be used in an equilibrium scheme by redefining them slightly. Youth would become sub-equilibrium. Maturity would represent equilibrium during that time when potential relief exceeded some necessary minimum value (such as, for instance, 300-400 feet) (Glock, 1932). And old age would mean about the same thing as a second, but different, equilibrium, developed while potential relief is being reduced to some value greatly below the minimum.

However, Davis had no such idea in mind. He specifically adopted the premise that the slope angle, on any given hill-side, is time-dependent: that is, that it becomes gentler with the passage of time, without the necessity of altering the processes which operate on it. Many geologists have reacted, either intuitively or otherwise, against this proposal. Penck incorporated what amounts to an equilibrium slope (and therefore an equilibrium form) in his system. The Stockwerk concept was, similarly, based on equilibrium considerations, although the present writer is not aware that these were spelled out in connection with the development of the idea. Lawson (1915), Bryan (1922), and a few others during the same period adopted the "parallel retreat" hypothesis, which is based on the equilibrium concept, even where not so stated.

Bryan's correlation of slope angle with rock type and fracture net, the work of Schumm (1955, 1956) and Smith (1958) on similar projects, the observations of Horton (1945), a preliminary statistical appraisal by Tanner (1956), and model and field observations by many others tend to support the equilibrium, rather than the time-dependent slope form. Smith stated that "each slope mean represents an equilibrium condition in which the slope has been adjusted to achieve a steady state between the resistivity of the material to erosion and the intensity of erosional processes."

DEPARTURE FROM EQUILIBRIUM

More recently, Tanner (1959, 1960) has shown that moment measures, such as skewness and kurtosis, can be used to advantage in geomorphological studies. Where plotted against each other (Figure 2), they permit identification and separation of at least seven distinctive landscape types. The data used for constructing a chart of this kind are hillside elevations (above mean sea level), cumulated from the lowest to the highest, and converted to percentages. Such an array of cumulated percentages, in each case totalling 100%, represents the shape or form of the area under study. If hillside elevations are distributed "normally" (that is, according to the Gaussian law), the skewness is zero, the kurtosis is three, and a plot of cumulated elevations on probability paper looks like the central inset.

An area which is predominantly upland, with some slopes, will yield a high positive skewness (such as 5 or 10) and a high kurtosis (perhaps 20 or more). It will plot, on probability paper, like the upper right inset in the figure. An area which is mostly lowland, with some slope, will have high negative skewness, and high kurtosis, and will plot like the upper left inset in the figure.

It will be seen that the insets can be interpreted directly; the bottom center inset, for example, represents upland-slope-lowland percentages of about 40, 20, and 40 respectively.

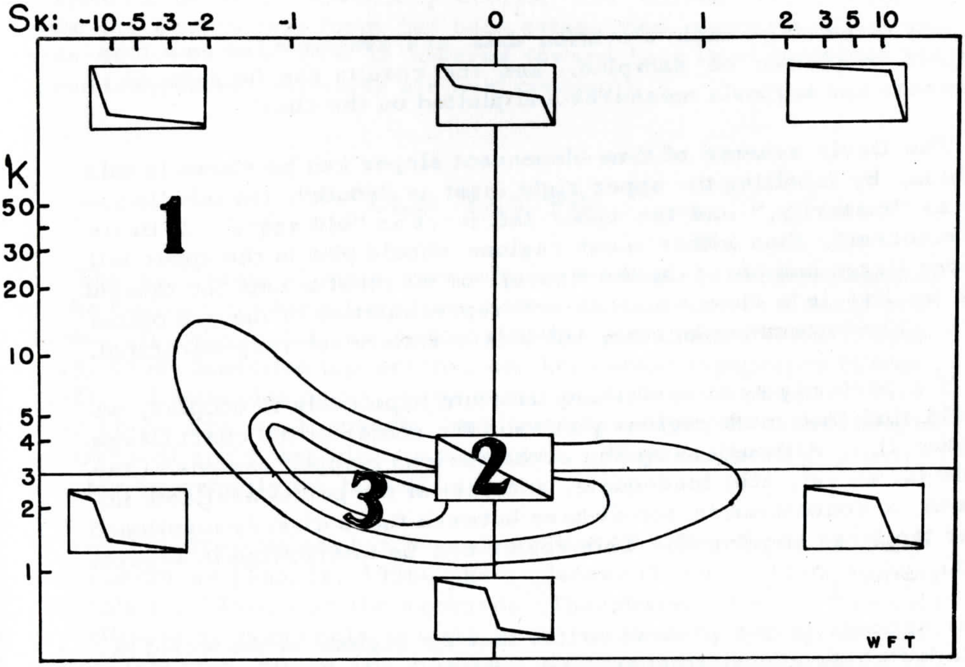

Figure 2. The skewness-kurtosis diagram, as used in geomorphology. Each inset is a probability plot, based on cumulated elevation figures from a specific area. On each inset, the probability scale occurs on the horizontal ordinate, and the elevation scale on the vertical ordinate; these scales are not detailed. The central inset (behind the large number "2") represents any region in which the distribution of hillside elevations follows the Gaussian (i.e., "normal") law, or can be transformed to follow the Gaussian. The upper right inset is mostly uplands, with some steeper slopes. The upper left inset is mostly lowlands, with some steeper slopes. The other insets show various combinations of uplands, slopes, and lowlands. In the Davis scheme, the upper right inset would be labelled "youth", the central inset "maturity" and the left inset "old age". These insets are shown here against a background chart where elevation skewness has been plotted against elevation kurtosis (Sk vs. K). Use of these two parameters permits comparison of any one region

with any other, or with the idealized insets. Most regions apparently fit in the crescent-shaped part of the chart which has been isoplethed near the large number "3". This concentration of data does not support the Davisian hypothesis, but rather lends credence to the equilibrium concept. For fuller discussion, see text.

Any area for which elevation data are available (as on a topographic map) can be sampled, and the results can be reduced to skewness and kurtosis measures and plotted on the chart.

The Davis scheme of time-dependent slopes can be shown in this fashion, by labelling the upper right inset as "youth", the middle inset as "maturity," and the upper left inset as "old age". If Davis were correct, then either most regions should plot in the upper left corner (large number 1 in the figure), or we must accept the thought that we live in a time which is not representative of the geological past. The latter may be true, but it is certainly not very attractive.

If a perfectly symmetrical equilibrium hypothesis is adopted, we should find that most regions plot near the center of the chart (large number 2). Although sampling of the various mapped regions of the world is, as yet, still inadequate, analysis of the points available indicates a concentration somewhere between those already mentioned (near the large number 3). This result can be interpreted in several ways.

It appears to the present writer that the regions of the world include both high-energy (that is, high potential relief) areas, and low-energy (low potential relief) areas, and that equilibrium forms are widely developed under both circumstances. A region having a single equilibrium form might look like the central inset in Figure 2. Whether high or low energy conditions were indicated could be determined from the standard deviation, or more simply, from the relief figure itself. A region marked by a major low energy equilibrium form and a minor high energy form might look like the upper left inset in the figure.

The negative skewness of the total of all areas sampled to date (large number 3, Figure 2) indicates that low-energy equilibrium (developed in areas of low potential relief) is more common than high energy sub-equilibrium (developed early in the histories of areas of high potential relief). The low numberical value for the skewness, coupled with the rather undistinguished kurtosis (about three) are taken to mean that high energy equilibrium is more common than high energy sub-equilibrium. Whether the high or low energy variety of the equilibrium form is dominant cannot be determined from skewness and kurtosis alone.

This interpretation is consonant with the basic assumption, here expressed, that slope form must be the product of materials, energy (expended in some specific process), and climate; and that time, once the equilibrium form has been established, appears only in the rate at which the form is lowered toward base level (provided the three independent variables are held constant).

CLIMATE TYPES

The four main climate types which contribute to the development of the equilibrium form have been listed above. The wet climate produces, typically, what has been variously described as selva (Thornbury, 1954), landslide topography, and knife-edge topography (Cotton, 1942). Landslides occur, to be sure, regardless of climate, wherever rocks are weak enough, and tectonic activity is great enough. In areas of truly wet climate, however, deep weathering provides greater opportunity for landsliding.

The hot dry climate has been described as producing the closed-basin pediment (Tanner, 1956), the esplanade (Lobeck, 1939), the erg (Thornbury, 1954), and the hammada (Thornbury, 1954). The cold dry climate is commonly thought to be marked by glacial or periglacial features, tundra, or steppes. The moderate climate is reported to be characterized by the open basin pediment (Tanner, 1956), savanna (Cotton, 1942), and rolling to hilly woodlands and plains.

Equilibrium forms for some of these types have been suggested by Cotton (1942). Our reluctance to recognize them, however, has stemmed from the fact that, in many parts of the world, the "types" do not seem to be "typical". For example, the rounded knob topography (tors, bornhardts, etc.) which is supposed to identify the savanna also appears on many definitely non-savanna types (such as the selva, the pediment, and the tundra). This is because the equilibrium form is not the product of climate alone. The materials available must be considered also. And one of their most important characteristics may be described under the term, directional weathering.

ISOTROPISM

In the sense of the preceding paragraph, rocks are either isotropic or aelotropic. This result obtains obviously and directly. It can be observed, in the field, on a small scale. Many blocks, boulders, and smaller rock fragments show weathering-banding which indicates that they are isotropic (weathering has proceeded equally rapidly in all directions). This phenomenon has been observed by practically all field geologists, on both curved and non-curved surfaces. As a general rule (but not invariably) there is no visible bedding, schistosity or foliation present. Such weathering bands typically maintain a constant "width" (that is, depth from the rock surface over a single block or boulder, and from boulder to boulder in the same lithology).

Isotropic rocks produce bornhardts, tors, monoliths, sugar loaves, etc. They are not limited to the savanna. The present writer has examined features of this kind from many parts of the United States where savanna conditions do not prevail.

Not all rocks are isotropic to weathering, however. Many examples are known where structure and/or stratigraphy control the weathering. Such rocks are aelotropic. As they weather in preferred directions they produce mesas, buttes, cuestas, hogbacks, and other similar forms. Two main classes of aelotropic rocks appear: those where beds or planar masses are horizontal, and those where beds (or planar masses) are inclined. The former give rise to the esplanade, mesas, and buttes of dry regions, and the latter to cuestas and hogbacks. Inclined aelotropic rocks, under savanna conditions, develop cuestaform topography much like they do elsewhere.

The general relationships between climate and directional variability are given, roughly, in Figure 3. This chart is not comprehensive, and the division lines shown in it are not sharply or narrowly drawn. Some distinctive landforms, such as dunes, are omitted because their development is not controlled by the common climatic parameters described in terms of moisture and temperature. Instead, they reflect availability of the right materials (sand-sized particles), plus windiness, and therefore constitute a special category. The various dune types have, however, equilibrium (depositional) forms.

Figure 3 likewise does not include coastal features. The latter are particularly complex, inasmuch as practically all forms of energy operate there. The gradient may be markedly different from what one might reason from consideration of the ground, or shallow sea floor, slope. A detailed discussion of some of these problems has been presented elsewhere (Tanner, 1959, 1960). The equilibrium concept is extremely valuable in working with them.

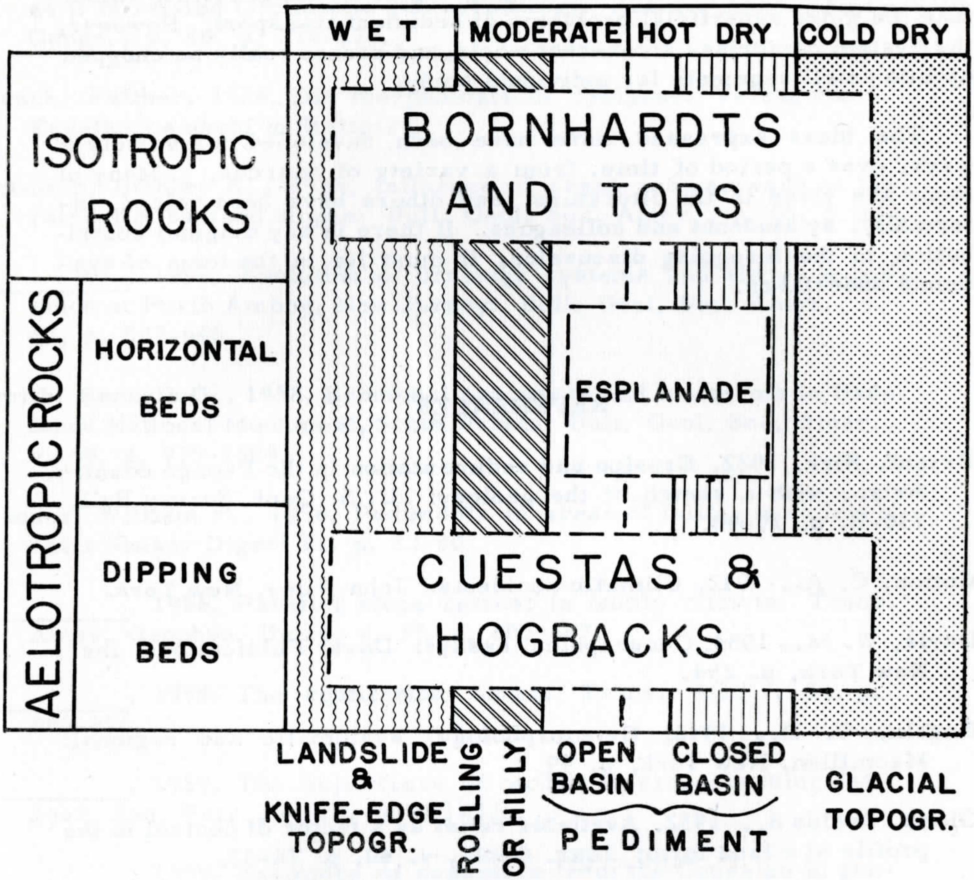

Figure 3. Plot of rock isotropism against the four main climate types (at top of chart). Vertical shading, and notes at bottom, indicate isotropic effects.

SUMMARY

The geomorphologist is concerned chiefly with the source and the gradient, although there are places (such as the Mississippi River delta, in the Gulf Coast geosyncline) where the sink is also of interest to him. The sedimentologist studies primarily the gradient and the sink. The stratigrapher finds that former sinks are of maximum interest. The structural geologist must consider all three components, although he may deal largely with rates of relative movemen in the source and sink, and changing angles on the gradient, rather than the more superficial problems of sediment transport. However, the system comprises a coherent whole, and cannot really be chopped up into small segments for individual study.

The ideas expressed here have been developed in a variety of ways, over a period of time, from a variety of sources. Many of them are given in the literature, and others have been voiced, informally, by students and colleagues. If there is any original contribution in the foregoing discussion, it must lie in the form of synthesis undertaken.

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