Methods of Mechanical Analysis of Sediments

Wentworth

NEW SERIES 117 OCTOBER 15, 1926

UNIVERSITY OF IOWA STUDIES

STUDIES IN NATURAL HISTORY

VOLUME XI NUMBER 11

METHODS OF MECHANICAL ANALYSIS OF SEDIMENTS

by

CHESTER K. WENTWORTH

PUBLISHED BY THE UNIVERSITY OF IOWA, IOWA CITY

Issued semi-monthly throughout the year. Entered at the post office at Iowa City, Iowa,
as second class matter under the Act of October 3, 1917

Wentworth
Methods of mechanical analysis of sediments

Wentworth
Methods of mechanical analysis of sediments

UNIVERSITY OF IOWA STUDIES IN NATURAL HISTORY

HENRY FREDERICK WICKHAM, Editor

VOLUME XI NUMBER 11

METHODS OF MECHANICAL ANALYSIS OF SEDIMENTS

by

CHESTER K. WENTWORTH

PUBLISHED BY THE UNIVERSITY OF IOWA, IOWA CITY, IOWA

METHODS OF MECHANICAL ANALYSIS OF SEDIMENTS

INTRODUCTION

Purpose of Mechanical Analysis

The mechanical analysis of a sediment or of any detrital material may serve a number of useful ends. The most obvious result of such analysis is the determination of the several sizes of particles which are present, and from these data the average size and the range of coarseness are at once apparent. A complete mechanical analysis, however, involves not only the determination of the sizes of particles which are present but also the proportions by weight or volume in which the several grades occur. And finally, as the third aim of mechanical analysis, there result the several grades of material, each separated from coarser and finer material and best adapted for study and preservation.

Knowledge of the sizes of particles which are present in a given sediment or artificial material is valuable in a number of ways. In the case of a natural sediment it may determine the name by which the geologist designates the material.[1] In cases where only rough conformability to specifications is required the knowledge of grades present in part determine suitability of the material for various technical uses such as the value of gravel for road metal, sand for glass manufacture, or the finer natural abrasive materials for their several uses. A determination of the several grades present is a means of checking the performance of crushers and separators used in various metallurgical and other commercial mineral operations and the suitability of the materials so prepared for the next stage in the process.

Commonly the proportions of the several grades are determined and these additional data serve much more refined purposes. Thus the geologist is enabled in many instances to deduce the mode of origin and the agent of deposition from a series of mechanical analyses of a certain type of sediment and in cases where this is not possible the data thus derived still serve in a valuable supplementary

---

[1] Wentworth, C. K., A Scale of Grade and Class Terms for Clastic Sediments, Journal of Geology, Vol. XXX, pp. 377-392, 1922.

way.[2] In other cases mechanical composition may serve as a means of correlating detrital formations in which fossils are missing or rare.[3] An increasing use is being made of mechanical analysis as a criterion of suitability of sediments for various commercial and engineering operations. Mechanical composition largely determines the value of materials used for filtering on a large scale, for the construction of earthwork dams and, to a lesser but still important extent, of materials used in concrete construction and of molding sand.[4] Likewise an increasing attention is being paid to mechanical composition as an important characteristic in writing standard specifications for both natural and artificial materials furnished on contract.

The value of mechanical separation into grades can hardly be overestimated either for critical study or for display and preservation. To the student investigating the petrology or mineralogy of sediments, well cleaned and graded materials are studied with an interest and an economy of time which is impossible with the natural material. For example, in the determination of minerals it is found that the bulk of the minerals of a certain sort or present in a certain form are found in a few grades only. The specialities in the several grades may thus be dealt with in the place where they are most important and where their relations are most clearly seen. There is an economy of attention and a proper perspective and basis for comparison when one is working with materials of similar sizes that is lacking when working with unsorted materials. This principle governs the plan of work in various industrial operations and explains the difficulty one experiences in turning suddenly from very coarse to very fine work of any sort. The desirability of grading materials by size has likewise been recognized by biologists in studying small shells and similar organic objects.

In similar fashion the display of sediments or other such materials is much more effective after grading and especially if the several grades present are displayed in proper order and proportion so as to give a vivid notion of the composition of the natural material.

---

[2] Dake, C. L., Missouri School of Mines, Bulletin, Vol. 6, No. 1, p. 152, et seq., 1921.

[3] Trowbridge, A. C., and Mortimore, M. E., Correlation of Oil Sands by Sedimentary Analysis, Economic Geology, Vol. XX, pp. 409-423, 1925.

[4] Littlefield, Max, Natural-bonded Molding Sand Resources of Illinois, Bull. Ills. Geol. Surv., No. 50, 1925.

THE METHODS IN USE

Two principal methods of mechanical analysis are in common use, screening and elutriation. Under elutriation is included the method of settling in still water, though some writers restrict the term to the rising current process of hydraulic classification.[5] A third method—that of counting—with several variations, completes the list of methods of mechanical analysis. It is unfortunate that a single rapid, accurate and convenient method is not available for the mechanical analysis of materials of all the degrees of coarseness which are common in natural sediments. Many of the natural sediments are of aqueous origin. Such sorting as these exhibit is the result of more or less perfect hydraulic classification in which density, size, shape and surface texture are factors. Because of this fact it has been pointed out that analysis by elutriation is the only satisfactory method of securing a separation which depends on these same factors and thus approaches closely the conditions under which the sediment was deposited. For the finer sediments the method of elutriation in one form or another is admirable, but practical difficulties arise in applying it to materials coarser than the sand grades.[6] For example, the settling velocity in water for a quartz pebble 5 cm. in diameter is about 5 meters per second. The separation of materials settling at rates of 5 meters per second in still water would involve prohibitive quantities of water and sizes of containers. Likewise the rising current separation of such grades is impracticable. In a tube of 30 centimeters diameter a velocity of 5 meters per second will discharge approximately 5700 gallons of water per minute. It is apparent that some other method for the separation of the coarser grades must be adopted. The use of sieves has been the most common expedient. Because of the cheapness and convenience of manufacture in a wide range of size of opening, woven wire sieves with square openings are the most practical. In using these the constituent particles are classified by cross-sectional size only; the density does not enter as a factor in separations and the shape only as it affects the size of the minimum square through which the rock fragments will pass. Thus in the same grade are found great variation in density, in volume, and in shape and the grade may consist of particles which will not exhibit similar behavior in streams or on beaches under natural conditions. It ap-

---

[5] Webster's International Dictionary.

[6] Holmes, A., Petrographic Methods and Calculations, p. 204, London, 1921.

pears to the writer that a separation on the basis of weight of the individual particles would come somewhat closer to the natural hydraulic classification and he has used this method of grading in connection with experiments in pebble abrasion but so far as is known this method has not been used for analysis and automatic methods for such weight separation have not been devised. In spite of its undesirable features the method of sifting in woven wire sieves, by virtue of its convenience, speed and relative accuracy, has come to be the standard method of analysis for the sands and coarser materials. For materials finer than about 1/4 mm. diameter sieves are less satisfactory because of the tendency of the finer materials to form aggregates and to lodge in the sieve openings. Wire cloth has been woven with openings somewhat smaller than 1/20 mm. but the finest mesh which proves practicable in the grade scale advocated by the writer is that with 1/16 mm. openings. This is the lower limit of the method of sifting and for finer grades elutriation or microscopic counting must be used.[7] The practical upper limit of elutriation may be set at one millimeter. Sediments containing grades from one millimeter downward may be handled wholly by elutriation; those of coarseness ranging from 1/16 mm. upward may be handled wholly by the method of sifting. It is apparent that many sediments cannot be analysed completely by either method alone. The need for a change from one method to another in the course of the analysis of these sediments is perhaps the most troublesome element in the whole field of mechanical analysis. If the sediment in question is composed wholly of particles of the same density and shape the problem of connecting the hydraulic grade scale with the cross-section grade scale at the point of change involves accurate determination of the hydraulic values of the particles at the lower limit of the smallest sieve grade. If it is desired to use a uniform notation throughout the analysis it is further necessary to determine either (1) hydraulic values of the several critical sieve sizes above the point of change in case a hydraulic notation is to be used, or (2) the cross-section values of the several critical hydraulic values in case the size notation is preferred. When the sediment which is to be analysed contains particles of various densities and shapes, the problem becomes not only much more complicated but is not capable of exact solution and the two types of grade scale must be joined by compromise, giving the larger weight to the shapes and densities

---

[7] Holmes, A., *Op. cit.*, p. 204.

which are present in the greatest abundance. Inadequate appreciation of the nature of the problem on the part of students of sediments in the past and the great difficulty of reaching even an approximate solution under standardized conditions has led to much confusion in this field and to the publication of many different combinations of grade scales and to great diversity of assumptions or determined values in connecting the hydraulic and cross-section scales.

This situation seems to have been the principal factor in the decision of certain investigators, notably Udden,[8] to extend the sieve scale downward by microscopic counting. This method, though to a less degree than that of elutriation, differs from the sieve method and must likewise result in certain discontinuity at the point of change to it from the sieve method. The method of counting, megascopic and microscopic, is applicable to the whole grade range of natural sediments and is undoubtedly in the case of a single critical sample the best method of making an accurate mechanical analysis now available, since by identifying the various constituents the density factors may be taken into account and the resulting analysis suffers from no very serious discontinuity if care is taken to use comparable methods in the megascopic and microscopic portions. Until more exhaustive investigations have been made of the effect of shape on rates of settling, this factor introduces unknown errors in the recognition of the natural hydraulic grades by the method of counting. Furthermore, counting is at best a very laborious procedure and is therefore hardly applicable to large numbers of samples. At the present stage of interpretation of mechanical analysis it appears to be more profitable to examine larger numbers of samples with considerably less theoretical accuracy by some reasonably expeditious method.

SCOPE OF PRESENT PAPER

In the early stages of any sort of investigation great diversity of methods results from the more or less independent work of different pioneer students. This is a most desirable condition for it results in the testing of many different types of procedure and in the exploration of the field of available technique. In later stages, however, the need of comparing results attained by different workers makes

---

[8] Udden, J. A., Mechanical Composition of Clastic Sediments, Bull. Geol. Soc. Amer., Vol. 25, pp. 655-744, 1914.

some degree of standardization imperative. The great diversity of methods used by pioneer workers is the result in large part of ignorance of methods used by others and of the consequent independent devising of methods.

The purpose of the present paper is to bring together in one place descriptions of some of the more important methods of mechanical analysis where they may guide students of sediments and sedimentation and help to eliminate some of the existing confusion. It is not to be expected that any one method will be used to the entire exclusion of others; this would be an admission that the study of sediments is stagnant or at the limit of growth. But on the other hand, the elimination of the more or less accidental differences of graphic plotting from right to left by some and from left to right by others, and the adoption of some equal ratio geometrical grade scale will be conceded by all as appropriate bases for standardization. In encouraging the adoption of the preferred methods the author has considered it wise to go into considerable detail in the description of the various methods and apparatus, and to supplement the descriptions with diagrammatic illustrations and tabular statements of procedure.

In its inception the present paper was planned as a joint paper by the writer and his colleague, Max S. Littlefield; the latter to prepare the part relating to elutriation, deflocculation and other methods dealing with the finer sediments. As work progressed it became apparent that the technique in this field was so much less well elaborated and, indeed, the purpose and value of mechanical analyses of clay grades so much in question that it was best to complete the present paper with the chief emphasis on the materials coarser than clay and leave the problem of finer materials until further studies make a more authoritative statement possible.

ACKNOWLEDGEMENTS

The author has been assisted from time to time in the testing of methods and apparatus by a number of students who have carried on their work in the Sedimentation Laboratory of the State University of Iowa. Experience in mechanical analysis has been gained as a by-product of other investigations, chief among which have been the studies of Atlantic Coastal Plain terrace gravels for the U. S. Geological Survey by the writer, and studies of Mississippi delta sediments for the War Department by M. S. Littlefield as assistant

to Dr. A. C. Trowbridge. More recently Mr. Littlefield has been engaged in a study of molding sands for the Illinois Geological Survey, in the course of which he has gained much experience in methods of analyses and sampling. To him and to a number of other graduate students at the University of Iowa the writer gratefully acknowledges his indebtedness for suggestions and criticism. For general encouragement and critical discussion of methods and purposes of the study of sediments during the course of studies mentioned above, the writer is especially indebted to A. C. Trowbridge, of the State University of Iowa, and to T. W. Vaughan and M. I. Goldman of the U. S. Geological Survey.

COLLECTION OF SAMPLES

SIZE OF SAMPLE

The size of sample to be collected for mechanical analysis depends on a number of considerations. If the sample is for a single analysis of a homogeneous fine grained material and no further examination is to be made, the amount collected may be small. If, on the other hand, the analysis is to be run in duplicate or the sample is of a coarse, heterogeneous material and the separates are to be studied by other methods, the amount must be much greater. If the mechanical composition of a single thin lamina of fine material is to be determined a small sample will be sufficient, and indeed in such a case an attempt to collect a larger sample is likely to result in the inclusion of material not representative of the lamina and to lead to less accurate results in the end. In commercial sampling it is usually desired to know the average composition of a certain deposit and in this case the materials of different beds or of different areas will need to be included in the sample in proportion to the amounts found on the ground in case a single sample only is to be analysed. In sampling a uniform horizontal series of beds which are unconsolidated this is most easily accomplished by cutting down a uniform channel from top to bottom. This results in a large sample. Any sample in which the amount of material is controlled by nonuniformity, either natural or artificial, may, after thorough mixing, be reduced in size by splitting to the limit imposed by the sizes of the largest constituents or by the purposes to which the sample is to be devoted.[9]

The size of sample needed for an accurate mechanical analysis bears a definite relationship to the coarseness of the sediment. In

---

[9] Milner, H. B., Introduction to Sedimentary Petrology, pp. 15-17, London, 1922.

general it may be stated that the sample should be large enough to include several fragments which fall in the largest grade present in the deposit. Several fragments may be interpreted as a number sufficiently large so that the probability of a serious accidental deviation from the normal number of such fragments in a sample collected by a reliable random method is small. This number depends in turn on the percentage of the whole which is included in the coarse grade and it is not practicable to adopt specific theoretical standards. It is important, however, that the collector appreciate the principle relating the size of sample to the sizes and abundance of the larger constituents. The following table based on a specific number and percentage of coarser fragments indicates in the second column the smallest size of sample demanded to insure satisfactory accuracy in determining the coarse grade. Several practical considerations are of importance. In general it is hardly profitable to collect less than 125 grams, even of a very fine material, if it is readily obtainable from the outcrop. At the other extreme it is rarely practicable for the geologist to collect samples as large as those demanded by the strict requirements of accuracy. Taking these several limitations into account in the light of experience both in collecting and in subsequent analysis, the scale of sizes given in the last column of the following table is presented as a working suggestion.

TABLE OF SUGGESTED MAXIMUM AND MINIMUM WEIGHTS OF SEDIMENT SAMPLES[10]

Coarse Grade	Ideal minimum to determine coarse grade.	Ideal maximum for convenient analysis in 6″ sieves[11]	Suggested amount of collected sample.
128–64 mm.	256 kg.		32 kg.
64–32 "	32 "		16 "
32–16 "	4 "		8 "
16– 8 "	512 grams		4 "
8– 4 "	64 "	1600 grams	2 "
4– 2 "		200 "	1 "
2– 1 "		25 "	500 grams
1–1/2 "		25 "	250 "
1/2–1/4 "		25 "	125 "
1/4–1/8 "		25 "	125 "
1/8–1/16"		25 "	125 "

---

[10] The first column gives the large amounts of coarse material demanded for valid determination of coarse grades. The second column indicates the amounts for the finer grades which are best adapted for sifting and weighing. The third column is a practical compromise from the first and second columns with amounts of the finer sediments increased to give additional material for checking or supplementary study.

[11] In case the collected sample is larger than the amount needed for analysis,

CONTAINERS

It is important in collecting samples of sediments for mechanical analysis to provide plenty of containers of ample size. All containers should be tight for the material to be collected and should be stout enough to stand much wear and tear. Loss from broken containers is practically always selective and remaining contents will be of little or no value in mechanical analysis. Cloth bags are most satisfactory for collecting dry materials in the field. They are durable and sufficiently tight if made of fine material and a number of them take up little space until they have been filled. Wet materials, and especially the finer clay sediments in which the original colloidal condition is an important characteristic, should be placed at once in air tight, sealed containers which are entirely filled with the sediment and contained water. Square or round glass jars of various sizes with aluminum screw tops may be obtained from dealers in scientific apparatus and are convenient for wet collecting. Ordinary glass fruit jars are nearly as good for the larger samples, somewhat less expensive and more readily obtainable in the field.

As a guide in ordering sample containers the following tables are presented.

TABLE OF CAPACITIES OF CLOTH BAGS
(Allowing length to tie readily at the top.)

Width and length Inches	Width and length Centimeters	Capacity by weight of dry sand
12 by 18	36 by 46	10 kg.
9 by 14	23 by 36	5 "
7 by 9	18 by 23	2 "
5 by 8	13 by 20	1 "
4 by 6	10 by 15	500 gm.
3 by 4½	8 by 11	200 "
2 by 4	5 by 10	100 "

TABLE OF CAPACITIES OF JARS AND TUBES

Type	Height	Outside diameter	Capacity by weight of dry sand.
1 qt. Mason	190 mm.	105 mm.	1400 gm.
1 pt. "	140 "	90 "	700 "
½ pt. jar	110 "	90 "	400 "
16 oz. Screw	150 "	85 "	800 "
8 oz. "	145 "	65 mm. square	400 "
Round bottom shell vial	110 "	30 mm.	35 "
"	60 "	12 "	6 "

---

split it down. In case, when analysing a coarse sample, the fines at any stage amount *in toto* to much more than the suggested maximum for convenient analysis for that grade, the analysis should be broken at that point and the combined and mixed fines split down to suitable amount before proceeding. The limit is not, of course, fixed or arbitrary, but in general amounts greatly in excess of those given should not be passed through the sieves.

NOTATION AND LABELING

Samples should be accurately labelled so as to indicate the exact locality, the field name of the sediment, the beds or part of the outcrop represented, the proper name of the formation, the method of sampling, the date and the name of the collector. The method of recording these data will usually depend on the form of the collectors field notes. The main desiderata are the same as for ordinary field notes; easy cross reference between the samples, the field notebook and the field map; from any one to either of the other two. The writer prefers to place only a number on the sample and to record all other data in the field notebook under the number. After trying a number of schemes for numbering and lettering notes and localities he has adopted the simple plan of numbering his field stations serially in Arabic numbers, starting from 1 at the beginning of each project. This system does not indicate automatically as do some others the map location of the station. It is necessary in using it to make and number the map location and to make such route notes for each day's travel, referring to the maps used, that another person can readily find the stations in turning from the notebook to the map. This slight disadvantage is more than offset by a number of advantages which are especially important when large numbers of samples are collected. In the first place, in the storage of samples and of the separates derived by mechanical analysis the Arabic numerical scheme is the only one which presents an entirely obvious sequence for arrangement. Systems of letters and numbers, map grating systems or page and notebook notations are all more complicated and less obvious and entail much more confusion if several hundred samples are being analysed and later studied in the form of several thousand separates. A second advantage is the ease with which notes, maps, samples and photographs are all handled in the same series of numbers. The notes and the map stations are complete; i.e., every number in the consecutive series is represented. The samples and photographs carry the numbers pertaining to the stations at which they were taken but there are usually stations at which no samples or photographs were taken and this series is a broken one. Every number which is present, however, fits into one place and *only one place* in the scheme. A third advantage is of importance to persons or institutions collecting large numbers of samples in connection with several projects. The several series of samples, each numbered from 1 up, may be combined in one decimal series by adding ciphers and key digits at the left. Thus in a five place system the first 5000, a twentieth of the whole, may be divided in any order as occasion arises into number allotments of 2000, 1000, 1000, 400, 300, 200, and 100. Such a system indicates clearly to custodians the position in the collections which should be occupied by the samples collected with a given project. Specimens numbered in the field with the station digits can readily have the project key numbers added at the left when an appropriate block of numbers has been assigned. The following tabulation will illustrate the principle:

00001	to	00999	Project A.
01001	to	01999	,, B.
02001	to	03999	,, C.
04001	to	04999	Miscellaneous minor projects.
04001	to	04099	Project D.
04101	to	04399	,, E.
04401	to	04599	,, F.
04601	to	04999	,, G.

Methods and Precautions in Collecting

A sample which has been properly collected is in every respect a miniature representative of the deposit from which it came. From certain types of materials such a sample is obtained with little or no difficulty but in collecting from most of the natural sediments great care is needed to guard against one or more sources of error. If the material is in place in its natural bedded or massive condition the portion which is exposed may be excessively coarse because of the washing away of the finer constitutents and retention of the larger pebbles or sand grains in the face of the bank. This is a common condition in vertical or steep gravel banks and leads to a false impression of the abundance of the pebbles as well as to error in the analysis in case a sample is collected without cutting away the surface pebbles. Gentler slopes may be the sites of accumulation of the finer constituents washed from above and samples taken here will show too high a percentage of the finer grades unless care is taken to dig well into the deposit before the sample is collected. In collecting from any situation it is necessary to collect all the material from a given portion of the mass. The accidental falling of material from the bank as the sample is cut away may be highly selective and result in abnormal loss in certain grades unless precautions are taken to catch all the material. In collecting coarse material from a bank a cloth spread to catch the material cut from the cleaned outcrop offers the best procedure. For finer material it is convenient to hold a scoop-funnel of the type shown in Figure 1 indirectly against the outcrop. The scoop and bag may be held with one hand and the cutting done with a hammer, knife, or other tool with the other hand. In collecting heterogeneous material in which great differences are readily visible to the eye it is desirable to decide, before starting to take a sample, what its limits shall be. This decision is best made by a strictly random method such as taking to a given depth all material covered by a square of cloth laid by chance over the outcrop or by taking all material within a given radius of a random point. Some such predetermined convention relieves the collector of disconcerting uncertainty in regard to retaining or rejecting the abnormal material which seems commonly to fall at the last moment or to lie just at the limit of the collecting area. Collecting gravel which is strewn over a beach or samples of pebbles on the surface is exceedingly difficult to perform in an unprejudiced fashion and the most rigorous and unswerving decisions in regard to the area to be covered and the sizes to be considered must be made before starting the collecting. Without these precautions it is inevitable that there will be selective errors based on shape, color, rock material, size or degree of exposure, some of which may be just the sort to vitiate conclusions based on subsequent studies of the sample.

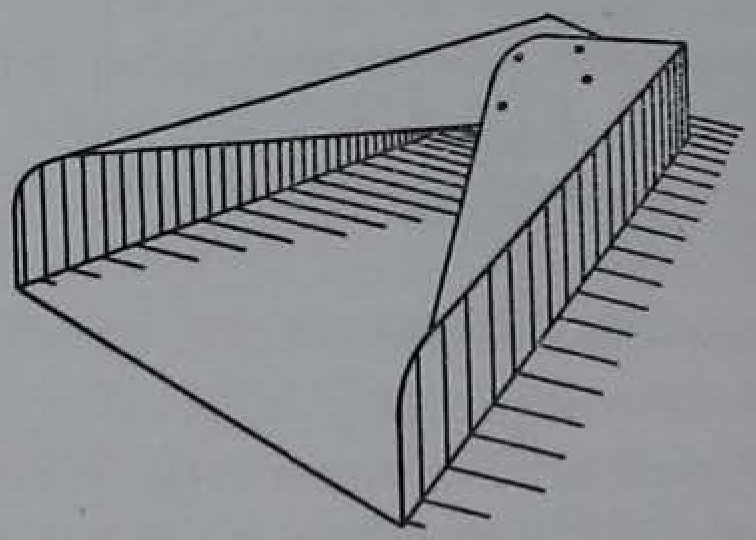

Fig. 1. Collecting scoop funnel used in filling bags at the outcrop.

If a sample is taken to represent a given stratum or other small portion of a deposit it is imperative that material from adjacent layers be excluded and the more so the more the materials differ from one another. In case a certain amount of contamination of any sort is unavoidable in practice, note should be made of the amount and probable effect of the foreign material. Samples of sand and gravel collected under water are likely to be washed more or less free of finer grades of collecting and this condition should be noted to guide later study and interpretation.

PROCEDURE IN SURFICIAL ROCK COLLECTING

The amount of equipment used in this type of collecting depends largely on the means of travel and the distance of the collecting ground from headquarters. Clean samples can be collected with a minimum of equipment if sufficient care is used, but if one is to collect large numbers of samples and is traveling by automobile the work may be done more readily and conveniently and with more uniformity if more extensive equipment is used. The prime requisite is the container. For most surficial collecting, especially if the samples are to be shipped a distance, the cloth bag is most satisfactory. If the pebbles of a gravel are weathered so as to be fragile or if it is desired to preserve the structure of a gravel or other sediment, it will be necessary to wrap the specimen carefully and perhaps to store it in a jar or some other sort of rigid container. For collecting loose sediments a hammer with the transverse chisel type of point is most convenient. If large samples are desired or if samples are to be secured by splitting material cut down from the face of a bank, a sample cloth is needed. This may range from 30″ to 6′ square according to conditions. If made of oilcloth or other smooth surfaced material it may be cleaned more completely, but for most dry sediments a cloth of drill or denim may be kept sufficiently clean and is more flexible and convenient to handle and is free from surface cracking.

Sheet metal scoops having flat bottoms and low vertical sides at one end and formed to a complete square or round aperture at the other end are very useful both in the field and in the laboratory. (Figure 1.) Several sizes of these having their end apertures corresponding to the sizes of bags used are desirable. The bag may be drawn over the aperture and the scoop and bag thus held with one hand against the outcrop for direct collecting. Pick and shovel are needed where considerable digging is to be done. In collecting material from thin laminæ or from the thin surface layers of beaches or rill deposits a small spoon or a putty knife is useful.

Two general types of collecting situations may be distinguished, the vertical or steep bank and the horizontal surface. The former is the more satisfactory from which to collect and in collecting from horizontal surfaces it is best to dig into the deposit sufficiently to expose its bedding if such exists and collect from the wall of the excavation.

The first operation in collecting from any situation is to clean the face of the outcrop and get back to fresh normal material. In doing this it is wise to clean a considerably larger surface than will be needed for the sample and if the sediment will hold together it is well to clean a channel around the part which is to be collected, leaving it protruding from the rest. In the case of horizontal beds in a vertical bank the strata above and below the layer to be sampled should be cut back if possible, leaving the latter ready to fall without contamination into the scoop, bag or cloth which is placed under it. In the case of a thick layer of uniform material being sampled this procedure may be reversed and the sample made up of several scoops or shovels full of material taken without discrimination from the bottom and sides of a clean hole, taking care that no material falls in from the edges. When a large sample of gravel is taken it is sometimes necessary to pin the sampling cloth tightly at the foot of the undisturbed outcrop, using a couple of spikes or surveyors tally pins.

Samples of heavy concentrates from thin surface layers on beaches and similar situations should be scraped from the surface with a spoon or knife using care not to include material from the underlying layers. In such samples, which are likely to be small in amount, very slight contaminations may introduce considerable errors in the composition.

Procedure in Indurated Rock Collecting

The same general principles hold in the collecting of indurated rock as for the loose sediments. If the rock can be disintegrated by treatment with acid or otherwise, it is better to collect a single large sample and analyse the whole of it in the laboratory than to collect a number of small loose pieces which may vary considerably from the normal rock in composition. However, it is commonly difficult if not impossible to disintegrate the rock by artificial means and analysis of a considerable quantity of the weathered debris from the rock is preferable to no examination at all of mechanical composition. If the composition is to be determined in part from study of plane polished surfaces or of thin sections, those cut normal to the stratification are preferable to those cut parallel to it and this consideration should be borne in mind in collecting. In the cases of coarse conglomerates, scale photographs of large exposures normal to the bedding may be much more valuable in determining mechanical composition than a small specimen which, moreover, offers difficulty in disaggregation.

PREPARATION OF SAMPLES

Disaggregation of Coarse Materials

No very well defined methods for the disaggregation of strongly indurated coarse sediments appear to have been described.[12] Conglomerates and sandstones which consist of noncalcareous grains cemented by calcium carbonate may be disintegrated by treatment with dilute hydrochloric acid. If a conglomerate is not too strongly cemented it may be broken up and a large fraction of the pebbles saved intact for analysis by sifting. This is best done in stages by hand, using a hammer only as necessary. In some cases disaggregation may be achieved by repeated heating and quenching.[13] Many gravels, tills and other coarse sediments are only slightly indurated by compacting or incipient cementation and only need thorough wetting, and maceration in water to disaggregate them. In such coarse gravels it is best to handle the process in stages as described in the section on analysis by sifting. The writer has found so much variation in the coarser sediments in the degree and kind of induration that the method of successive fractionation and carrying on the disaggregation by hand, either with the fingers or with a wood or rubber pestle, seems to be as satisfactory as any.[14] In breaking up dry aggregates in sands it is convenient to rub them on a white paper card with the fingers successively removing the fines and changing to fresh cards. The soiling of the card, while it means slight loss, gives a vivid idea of the progress achieved and enables the analyst to follow the process closely. Shaking in a vigorous mechanical shaker disintegrates dry sediments to a considerable extent but can hardly be said to complete the process nor to work successfully on material which would not yield much more readily to wetting and washing.

After a large sample has been mixed with sufficient water to make a soft mud and has been macerated by hand the coarse particles can

---

[12] Cayeux, L., Introduction a l'Étude Pétrographique des Roches Sedimentaires, Paris, pp. 4-5, 1916.
Hatch, F. H., and Rastall, R. H., Textbook of Petrology, The Sedimentary Rocks, p. 341, London, 1913.

[13] Cayeux, L., *Op. cit.*, pp. 4-5, 1916.

[14] Dake, C. L., *Op. cit.*, p. 156.

be taken out by washing the whole on the appropriate sieve. Fine silts and clays of the matrix will reaggregate in drying and analysis is much expedited if a small sample of the fines is reserved before wetting the material so that the fines of the wetted sample may be rejected without drying.

SAMPLE SPLITTING

The splitting of a sample, though it may consist in the establishment of several equal similar parts, usually consists in the separation from the larger sample of one small part which is as nearly as possible identical in composition and other characteristics with the main sample. It may be practiced for a number of purposes among which are the following: (1) Reduction of the size of a large composite or heterogeneous field sample to form the collected sample for the laboratory. (2) Removal from a large sample of one of more normal small fractions for analysis or other study. (3) Successive reduction of fines in the course of analysis. In working with sediments one of the first lessons that is driven home is the strong tendency that exists through the operation of various physical and chemical factors for like materials to become segregated. In splitting samples for mechanical analysis this tendency will be met on all sides and must be largely overcome if success is attained. Not all the details of such segregation are known but a few examples will serve to illustrate the extent to which the tendency is everywhere present. If a small quantity of sand with a few very large grains is shaken in a bottle it is seen that there is a certain amount of separation on the basis of size. When a similar sand is poured from a parellel-sided scoop it is noted that the coarser particles are more abundant adjacent to the sides. If it is poured through a funnel the central portion of the stream differs from the peripheral portions. The sliding and rolling of a heterogeneous sediment down the sides of a pile results in segregation which is apparent to the eye. From these few examples, which may be multiplied almost indefinitely by anyone who will spend a few minutes on a sandpile, it is readily seen that detrital material in which there are diverse sorts of grains cannot be handled without putting in operation some of the factors which bring about segregation. It is equally evident that these tendencies, unless studious attention is given to the problem of thwarting them, will result in abnormal fractions which will vitiate any results obtained from their study.

Most of the splitting or quartering devices which are commonly used are based on the idea of establishing two nearly equal portions by throwing alternating small portions or streams of flowing material into each. Such devices work satisfactorily if the quantity of material is large in proportion to the size of the larger constituents and if there is a considerable number of these. The type known as the Jones sampler is constructed on this principle and does very satisfactory work. The writer has purchased scoop samplers in which the material is poured on the five-channelled scoop from the solid scoop. The material falling between the channels constitutes one fraction and that falling into the channels another. The solid scoop furnished with some of these outfits is of the same width as five channels and four spaces; thus the abnormal edge portions from the solid scoop both fall into the channels and therefore into one fraction, whereas one should fall on a channel and one on a space. The user of such apparatus must guard against poor designing of this sort since the makers are not always attentive to the correct theoretical principles. Large samplers of the Jones type will do satisfactory work on coarse material with sufficient amounts of material. In splitting small samples of coarse material it seems permissible, and in fact essential, that the coarser grade and perhaps the next be separated out on a sieve and separated by inspection into as many equal and comparable portions as may be required and these portions added to the fractions which have been established by splitting by one of the automatic methods. For any grade of large fragments in which there are so few pieces that they may readily be inspected at a glance this method of splitting is better than one which depends on the laws of probability since these operate to the end here desired only when numbers are large.

The method of splitting known as quartering, as applied to the collecting of coal and ore samples, consists of the formation on a sample cloth of a conical pile of well mixed material which is cut into quarters by two right angled separations and the alternate quarters rejected. The remaining two quarters are again mixed by lifting and rolling the material on the cloth, alternately forward and backward from left and right. A new conical pile is again quartered as before. The procedure is continued until the sample is reduced to the size required. After trying this method with gravels the writer is of the opinion that it is much less successful in maintaining normal fractions for other kinds of analysis. The technique of coal sampling specifically requires crushing of the large sample to a half inch mesh which not only insures that there be a large number of fragments but also that large fragments be eliminated. The main purpose of gravel collection for mechanical analysis forbids the use of these two principles which are essential to the quartering method. The latter method works well with relatively homogeneous materials, but these are also well handled by most of the other methods.

A coarse sediment which has been well mixed by stirring and beating in a pan or on a cloth may be split with fair accuracy by throwing successive spoons or scoops full into alternate fractions as it is transferred from the pan or cloth. In this method care should be taken to avoid the systematic dipping of the spoonsful for the two fractions from different parts of the original mixture. The spoon or scoop should be filled quite as monotonously as possible from the mixture and emptied alternately to one side and the other.

Well mixed material which is poured in a broad stream from a pan is reasonably well split if the stream is made to flow half into one container and half into another adjacent to it. The stream should be made to flow symmetrically with the edges as nearly as possible.

It will be noted that nearly all the methods mentioned involve splitting the sample into halves and then one of the halves into quarters and so on. This is an essential part of the process. Any attempt to separate the sample into a large and a small fraction at once is likely by the nature of necessary devices to bring about some segregation favoring the accumulation of coarser material in one fraction or the other and vitiate the results.

ANALYSIS BY SIFTING

General Principles

In practice, analysis by sifting can be applied to the separation of sediments down to a fineness of about .05 mm. or .002 inch. From this size up to 10 cm. or about 4 inches, sifting can be conveniently accomplished in a series of testing sieves. Cobbles larger than this size are not ordinarily present in numbers in the samples analysed by the geologist and can be discriminated by individual measurement.

Some investigators in the past have advocated the use of sieves with round holes. These have the advantage that the sizes of the openings can be determined with great uniformity and that they may be readily made from sheet metal without elaborate special equipment. It has also been urged in their favor that a round hole is naturally more appropriate for the separation of the somewhat rounded particles than is any other shape of opening. In spite of these considerations the woven wire sieve with square openings has so many points in its favor that it has been generally adopted. Woven wire cloth is now made in a very great variety of sizes of opening, and diameter, and material of wire. Double crimped wire cloth keeps its original uniformity of spacing so successfully even with considerable rough handling that one of the former objections to the woven wire sieve has been overcome. The woven wire cloth can be made with much smaller openings than is practicable in the sieve made by punching or drilling round holes in sheet metal.

Some workers advocate the use of bolting cloth in clamp rings because of the ease with which new and clean cloth may be inserted. This method is doubtless of value when samples of sands of diverse sorts are to be studied for mineral content and it is desired to use extreme care to avoid contamination, but it seems hardly applicable to mechanical analysis to a grade scale of the sort suggested below.

As to the shape, it is probable that the round hole should be regarded as slightly more appropriate. However, since the minor cross-sections of most of the particles passed by any sieve are neither round nor square but more or less intermediate, it is probable that the difference in amount between the material passed by square and round opening sieves of the same diameter of opening, is very small. To be sure, the writer does not consider that analyses made in the two types of sieves would be interchangeable but merely that in the proportions of materials in successive grades one type of analysis is probably as good an approximation to the ideal hydraulic classification as is the other.

Choice of Grade Scale

The ideal representation of mechanical composition is a smooth curve showing the continuous distribution of sizes in their proper proportions from one end to the other of the range. Such a result is only to be attained by careful individual measurements on all the constituent fragments of the material in hand. Except for purposes of illustration or investigation as applied to a very limited amount of material, such procedure is not practicable and less laborious approximate methods must be chosen. The most obvious scheme is to divide the material into classes, determining the amounts in the several classes and thus indicating the distribution of the material in point of sizes of particles. If a large number of classes is established the results will approach those attained by individual measurements, but at the same time the operation becomes more time consuming. Whether a large number of classes of small range between their upper and lower size limits or a small number of large range are to be used must be determined according to the use to which the analysis is to be put and whether the greater expense of the former alternative is justified by the greater accuracy.

In choosing the classes into which the material is to be divided the limits of the several classes may be set according to a number of different considerations. In the case of materials for commercial use certain definite size limits governed by precedent or the capacity of equipment may be the critical limits in the analysis. Too often, in the case of geologists making mechanical analyses, expediency has governed and the grade scale has been determined by the series of sieves which chanced to be available with little attention to the fitness of the several size limits. The result has been that analyses have been made to a great variety of grade scales, many of which were ill adapted to the purpose in hand and all of which, because of the great variety, have hindered direct comparison. No argument is needed to indicate the great desirability of the use of the same grade scale by investigators who are working in the same general field, such as geology. In choosing the scale for general use it is well to consider those which have been used in the past. These are of several sorts as follows:

In the following table are given four types of grade scales which have been used in making mechanical analyses.

TABLE OF GRADE SCALES[15]

A	B	C	D
1.000″	1.000 mm.	2.33 mm.	8. mm.
.500″	.500 ”	1.66 ”	4 ”
.250″	.250 ”	1.17 ”	2 ”
.100″	.100 ”	.833 ”	1 ”
.050″	.050 ”	.589 ”	1/2 ”
.025″	.025 ”	.417 ”	1/4 ”
etc.	etc.	.295 ”	1/8 ”
		.208 ”	1/16 ”
		.147 ”	1/32 ”
		.104 ”	etc.
		.074 ”	
		etc.	

---

[15] Dake, C. L., *Op. cit.*, p. 152. Holmes, A., *Op. cit.*, p. 197.

These scales are tabulated in this form not to show comparisons between them but to show the ratio and starting point characteristic of each. Scales A, B, and D have simple integer starting points, one inch, one millimeter and one millimeter respectively. Scales A and B are hybrid scales in which two different ratios are used to secure an approximately uniform ratio and at the same time to make every third grade limit coincide with a decimal submultiple. Scales C and D are equal ratio scales (within limits of error in construction of sieves), the ratios being the square root of 2, and 2, respectively. Scale C starts from the exhaustively calibrated 200 mesh sieve used as the basis of fineness specifications of Portland Cement. Scale D combines the 1 millimeter starting point with a uniform ratio of 2.[16]

There have been numerous variations of these types used in practice and there are a number of nonuniform but approximate geometric scales represented by the systems of sieves in which the coarseness is designated by the number of meshes to the inch. Since in the past and to some extent at present the size of wire used in making these sieves has not been uniform there is much variation in the actual opening sizes and a number of different grade scales result.[17]

In too many instances in the past and occasionally even at the present time the sizes are indicated only by stating the mesh, a designation which is next to useless unless the critical data are given elsewhere in the paper and in that event needlessly cumbersome.

In all the scales which have been used in the past there is tacit recognition of the essential correctness of the constant ratio of geometrical scale. The arguments in favor of such a scale have been stated by the writer and others elsewhere and need not here be repeated.[18] Several possibilities present themselves in the choice of ratio, of starting point and of system of mensuration. Scientific work is now practically all carried on in metric units and this system seems best adapted to the mechanical analysis grade scale. One of the cardinal points of the metric system is its expansion on the

---

[16] Cayeux, L., *Op. cit.*, pp. 34-36, Paris, 1916.
Mohr, E. C. Jul., Bulletin In Départment de L'agriculture aux Indes Néerlandaises, No. 16, Buitenzorg, 1910.

[17] Milner, H. B., Introduction to Sedimentary Petrography, p. 18, London, 1922.

[18] Wentworth, C. K., A Scale of Grade and Class Terms for Clastic Sediments: Journal of Geology, Vol. XXX, p. 382, 1922.

decimal basis. Desire to use certain of the simple decimal fractions has led to such scales as B in the table above. Scales such as the following in which the ratios are small integer roots of 10 have been suggested by various investigators but so far as known to the writer have not been used in practice.

Ratio $\sqrt{10}$
E. 10.000 mm.
3.162 ''
1.000 ''
.3162 ''
.1000 ''
.03162 ''
.01000 ''

Ratio $\sqrt[3]{10}$
F. 10.000 mm.
4.641 ''
2.154 ''
1.000 ''
.4641 ''
.2154 ''
.1000 ''

These scales have the advantages of return to the submultiples of ten at uniform intervals and that the number of decimal sequences to be carried in mind is small. On the other hand, it is impossible to express them in common or vulgar fractions.

The scale made up of multiples and submultiples of 2 starting from 1 millimeter is probably most readily visualized of all. (Scale D.) The ideal scale would be possible if our system of numeration were a sexadecimal system instead of the arabic decimal system. Then we should be able to use halves, quarters and eighths of the

TABLE I

THE GRADE TERMS

The Pieces	The Aggregate	The Indurated Rock
Bowlder 256 mm.	Bowlder gravel	Bowlder conglomerate
Cobble 64 mm.	Cobble gravel	Cobble conglomerate
Pebble 4 mm.	Pebble gravel	Pebble conglomerate
Granule 2 mm.	Granule gravel	Granule conglomerate
Very coarse sand grain 1 mm.	Very coarse sand	Very coarse sandstone
Coarse sand grain 1/2 mm.	Coarse sand	Coarse sandstone
Medium sand grain 1/4 mm.	Medium sand	Medium sandstone
Fine sand grain 1/8 mm.	Fine sand	Fine sandstone
Very fine sand grain 1/16 mm.	Very fine sand	Very fine sandstone
Silt particle 1/256 mm.	Silt	Siltstone
Clay particle	Clay	Claystone

fundamental sexadecimal ratio and combine simplicity in visualization with simplicity of computing and notation.

The best compromise at present possible seems to be the use of the geometrical ratio-scale which may more simply be designated as the 1-2-4-8 mm. scale. The engineer scale which is based on the highly standardized but arbitrary size of opening in the 200 mesh sieve seems to the writer to be of too arbitrary a character and to entail needless complication in the decimal fractions by which the several limits must be designated. The names and limits of the several grades established by the 1-2-4-8 mm. scale are indicated in the table below previously published by the writer.

Equipment

The following outline indicates the range of equipment which is convenient in analysing sediments of sifting.

Sieves and accessories	Fitted sieves Covers Pans Blank sieve rings Wire squares Mechanical shaker Timing clock
Weighing apparatus	Balance, beam Balance, portable assay Balance, spring Graduated cylinder
Handling apparatus	Bag funnel scoops Tube funnel trays Metal pans Spoons Funnels
Splitting apparatus	Sample splitter Scoop Pans, square

Storage accessories	Cloth bags Screw top glass jars Metal pill boxes Glass specimen vials Corks Gummed labels Tube blocks
Washing apparatus	Jars and cylinders Rubber tubing Glass tubing Rising current washers
Miscellaneous accessories	Brushes Squares of paper Rubber stamps for notebook tabulating

Testing sieves consisting of woven wire cloth soldered into substantial stamped brass rings may be had from a number of makers. Some of these makers[19] are in a position to furnish sieves with openings conforming very closely to the scale here recommended when so ordered. These sieves are made so as to fit tightly one above another and are available in several diameters and heights. The writer has found that two sets, an eight inch series running from 64 to 2 millimeters, and a six inch series running from 1 to 1/16 millimeter are convenient since it is rarely desirable to run the analysis of a sediment ranging from 32 to 64 millimeters down to 1/8 mm. or less in one stage. Another set of six inch sieves running from 8 mm. to 1/16 mm. is convenient for those samples which lie in this range and may best be run in one stage. The six inch sieves are quite large enough for materials under 1 millimeter. In traveling, the individual six inch sieves can be packed in the spaces of the 8 inch series with much saving of space.

A pan and cover are essential with each set of sieves and an extra pan or two are very convenient when handling the individual separates while leaving the main sieve pile standing by. Blank sieve rings, which can be obtained by special order from the makers, are useful in increasing the capacity of any given sieve in handling large samples of the coarser gravels. In ordering these one should

---

[19] Newark Wire Cloth Co., Newark, New Jersey; Multi Metal Co., 799 East 139th St., New York City; W. S. Tyler Co., Cleveland, Ohio.

specify that they be crimped together and in every way completely assembled except with the wire cloth left out. When analysing sediments containing a few fragments larger than the largest grade isolated by the sieves, several large wire squares conforming to units of the grade scale are useful in testing these large pieces.

If large numbers of analyses are to be made a mechanical shaker is almost indispensable. The accuracy of separation is very greatly increased, results are standardized to a degree impossible in hand shaking, and very heavy samples may be handled in one stage which in hand shaking would have to be worked through grade by grade. With an automatic timing clock such an instrument accomplishes in a day's time shaking which would take at least a week by hand methods and at the same time leaves the operator free to perform the weighing and other operations of analysis. Mechanical shakers may be purchased from the makers or may be constructed in any well equipped machine shop. A shaker should be so designed as to combine lateral and rotary motions with rather vigorous jarring.

The balances used in mechanical analysis should be of the substantial laboratory sorts rather than precise analytical balances, since convenience, speed of operation and general staunchness are of more importance than great accuracy. Those of the three beam design with sliding weights by which the tens, units and fractions of grams are determined are satisfactory. Small compact portable assay balances are convenient for field use with small samples and spring balances have been used by the author in field analysis of coarse sediments. In working with rather homogeneous materials, such as sands of low size range in the field, it is probable that proportions could be determined with adequate accuracy by volumetric means, though the writer does not know that this method has been used in practice.

If much analysis is to be carried on several types of scoops and funnels will be found useful and may be readily made by any sheet metal worker. The funnel scoop shown in Fig. 1 is convenient in filling bags from the outcrop or from sieves or pans. Low-sided square or triangular trays slightly larger than the sieves and having one open corner are convenient in transferring sand grades from the sieves to the glass vials in which they are stored. An assortment of spoons and funnels adds to the convenience of handling.

If large numbers of samples are to be analysed they are handled most expeditiously by separating operations and several must be at various stages of completion in the laboratory at the same time. In this case many containers will be needed for temporary use. Small metal pill boxes are useful in this connection and for the larger and coarser separates round flat-bottomed pudding pans or basins with flare sides are recommended. These are easily cleaned, will withstand the moderate heat used in drying sediments, and by nesting many of them may be stored in small space when not in use.

One or more sample splitters will be needed and if there is a great range in the coarseness of the samples handled these should be of both large and small sizes. The Jones sampler is to be recommended or for combined field and laboratory use a folding splitter based on the same principle will be more convenient. A number of square pans should be provided for use with the splitter.

In the study and subsequent storage of sediments which have been mechanically analysed large numbers of containers are needed. Since many of the materials are fine grained they must be stored in tighter containers than are needed for many other types of rock specimens and like other specimens for scientific study and reference, must be carefully labelled. If permanent storage shelves or cases are available screw top glass jars are the most satisfactory containers for the larger samples. These are rather expensive in large numbers and it may be necessary to use cloth bags for these samples, and in any event the latter are preferable for field collecting. Glass shell vials are convenient and inexpensive for storing samples of materials not coarser than 8 mm. up to 25 or 50 grams in amount. These may be had in various sizes and are closed with short corks and stored vertically in holes in wood blocks. The writer has found that it is more satisfactory to design the blocks and case drawers so that a certain number of the blocks fit in each drawer than to design a single large perforated tube holder for each drawer. With the former scheme a small number of vials together with the block may be removed for inspection. In the laboratory at the University of Iowa each block accommodates 50 one-half inch vials in 5 rows of ten each. Each drawer of a case accommodates eight blocks in 2 tiers of 4 each, thus storing a total of 400 tubes one-half inch in diameter and two inches long.

In washing sediments an assortment of jars and cylinders and glass and rubber tubing are convenient. In a laboratory in which much mechanical analysis is done a rising current washing machine as a permanent installation will save the labor incident to rinsing the various sediments by hand methods.

Several brushes with soft bristles are useful in transferring fine sediments from one container to another and may sometimes be used in cleaning fine sieves. Squares of paper of several sizes will be found of occasional use even in a laboratory well equipped with containers of various sorts. In recording the results of analysis a rubber stamp bearing in a vertical column the designations of the several sieve grades is convenient in blocking out the entry in the notebook.

PROCEDURE

In describing the procedure of sifting it will be most convenient to follow an order which is mainly chronological, starting with types of analysis of coarse sediments which are sometimes carried out in the field and proceeding thence to the laboratory technique.

When a sample of coarse material ranging to 64 mm. or more and amounting to 30 or 40 kilograms has been collected on a sampling cloth and is not needed for exhaustive laboratory study, a part of the analysis may well be accomplished on the spot. The sample is first weighed as a whole, using a spring balance attached to the four corners of the cloth. The known weight of the cloth should be recorded along with the gross weight. Then, working on the cloth, all pebbles and cobbles over a convenient sieve size should be separated from the finer material. In many instances this separation can be accomplished without attempting to pass all the material through the sieve in question but merely working through the material and testing doubtful pieces on the sieve. The coarser fraction should now be cleaned, if need be washed and dried, run through the coarse members of the sieve series and then separates weighed by spring balance or placed in bags for laboratory weighing. The material washed or cleaned from these fragments may be discarded if most convenient rather than added to the fine fraction. If desired, measurements of shape and notes of lithology and color of the larger separated cobbles may be made and after weighing they may be discarded.

The fine fraction remaining on the cloth which usually amounts to a large percentage of the whole sample and which is relatively much more homogeneous than the original sample, may now be quartered or otherwise split down to a sample of size appropriate to the coarseness of the larger remaining fragments. If, for example, the 4 mm. sieve was used in making the primary separation the fine fraction may be split down to about 1 kilogram and the remainder rejected.

The part retained will be weighed and analysed in the laboratory. The total weight of the fines below 4 mm. is determined as the difference between the total sample and the total of the cleaned grades above 4 mm. It will be noted that the only operations which must be carried out at the outcrop are the weighing of the total sample, the separation of the sample at 4 mm. or any other convenient limit, and the splitting of the fine fraction down to portable size. In many instances the coarse grades will not be of great weight and the sample will be reduced in weight by as much as 75 or 80 per cent by throwing out the bulk of the fine fraction in the manner described. Furthermore, in order to do this no more equipment is needed than a single sieve or in a pinch a single accurate wire square.

In analysing a large sample of coarse sediment in the laboratory, the process should be carried on in stages in a similar fashion to the field procedure. If the material is fairly dry and not extensively aggregated, the 2 mm. sieve may be made the separating limit; otherwise a coarser one must be chosen. The entire sample is poured on the pile of sieves at one time if it is not too bulky. There may be insufficient room in the pan under the 2 mm. sieve for the fine fraction, in which case this will need to be successively removed. Coarse separates which are too large in bulk for one sieve space may still be retained by adding a blank sieve ring to the pile at the proper place. After all the material has been added and the pile has been shaken to secure a rough separation into grades and determine the approximate amounts, it is ready for the final shaking by hand or in the mechanical shaker. If the sample is dry and clean enough so that practically no fines will remain with the coarse grades as aggregates or incrustations, the whole sample need not be weighed before starting the analysis but in most cases this should be done.

If a mechanical shaker is available the shaking may be very quickly accomplished. If hand shaking is necessary the separate coarse grades are best shaken one at a time, using a cover and pan with the single sieve and starting with the coarsest grade. It is not practicable to establish any standard time of hand shaking for materials of this sort. With a sieve containing 5 or 10 eight to sixteen millimeter pebbles the completion of the sifting is apparent by inspection. As one proceeds to finer grades the end of the process is less sharp. Since the condition of sediments varies so greatly the best practice seems to be to continue shaking until the amount coming through the sieve is negligible for the purpose in view.[20] This is best determined by emptying or changing the pan after the major part of the fines has come through and shaking successively over an empty pan for a number of equal short periods. For fine sediments the completion of the sifting process is a practical impossibility, either by hand or by machine, and the end point must be determined according to the accuracy desired. The writer has used a period of 5 minutes for machine shaking on a series of coarse sediments and achieved a satisfactory separation for his purpose. The subject of accuracy will be considered more at length in the section on sources of error below.

After shaking, the coarse grades should be cleaned and weighed. The fine fraction must be weighed if the total sample weight was not determined or if the process is to be checked. This portion is then split to a size suitable to the size of its coarser grades. The analysis of a part of the fine fraction is accomplished in a manner similar to that described above. The principal difference is that in shaking by hand a larger part of the whole shaking may be done while handling the entire pile of sieves. Any sediment in which a considerable number of lumps or aggregates withstand the shaking process and remain with coarser grades should be washed or otherwise disaggregated. By weighing the whole sample and determining total fines by difference the more troublesome part of the washing process, the recovery of the fines, may be eliminated provided a small fraction is retained before starting the washing process.

No method of cleaning sieves is known which is rapid and effective. Some of the grains may be removed from the sieves by rubbing from the bottom side with a cork. Jarring or striking the ring with the hand in a direction diagonal to the wires will dislodge some but not all of the grains. A stiff brush may sometimes be used to advantage. Complete cleaning is achieved only by using a fine-pointed implement on the individual grains and taking care not to injure or displace the wires.

In making critical mineralogical studies the best procedure appears to be the use of bolting cloth or of small wire sieves such as 2 inches in diameter which one may keep absolutely clean by going over each sieve with a pointed tool.

The cleaned separates should be weighed on removal from the

---

[20] Goldman, M. I., Petrography and Genesis of the Sediments of the Upper Cretaceous of Maryland, p. 121, Baltimore, 1916.

sieves and then rejected or stored as the case may be. In general, weights should be determined to the order of the nearest 1/1000 of the whole sample analysed in the given stage. For very careful work in checking technique or with very homogeneous material somewhat more accurate weighing is desirable.

The amount of material needed for most satisfactory analysis varies somewhat with the composition of the material as well as with the coarseness. The amounts indicated in the last column of the table on page 10 are minimum amounts for material down to about 8 mm. Below that limit the amounts most convenient for analysis are shown in column 2 of the table. It may be suggested in general that the material lodging in any one sieve should be small enough in amount so that at least half the sieve surface is free at the end of each shaking oscillation. Sifting is a very slow and probably much less accurate process when the material on a sieve covers it deeply throughout the shaking.

The annotated computation outlines given below in the section on computing and plotting will serve as tabular summaries of the analysis procedure under several different conditions.

SOURCES OF ERROR

A mechanical analysis is a means of determining the mechanical composition of all or part of a sedimentary deposit. If the composition shown by the analysis is not identical with that of the deposit the analysis is in error by the difference. The composition shown by analysis may be accurate as representing the sample from which it was made and still very inaccurate as representing the deposit from which the sample came. A tabular synopsis of the various sources of error in mechanical analysis is given below.

Errors resulting from the geologist's inability to locate the sample properly are probably large. Especially if the sample is taken for the purpose of representing the typical composition of a deposit, it is likely to fall short of its purpose. The writer believes that there is a strong tendency in attempting to collect a *typical* specimen to collect what is more properly an *ideal* specimen. Other errors of the collecting process can be largely reduced by care in the technique. It is believed that with the present excellence of woven wire cloth errors due to variations in sieve openings from uniformity or from the ratings of the makers are relatively small and negligible compared to the errors arising from the inability of the geologist to collect, even from the same outcrop at different times, two identical samples. Elaborate tests of the performance of a series of sieves made by a reliable maker do not seem to the writer to be crucial in assuring the reliability of analyses made thereby when so much larger errors almost without exception are present as a result of unknown infelicity in the choice of the sample. In the case of the standardization of the 200 mesh sieve for engineering specifications the situation is quite different for here a highly uniform artificial material is being handled of which the mechanical composition as delivered is critical.

ERRORS IN MECHANICAL ANALYSIS

	Source	Result
COLLECTING	Sample not well located.	General error.
	Sample too small.	Large errors in coarse grades.
	Outcrop not well cleaned.	Increase in either fine or coarse grades.
	Selective accidental loss in collecting.	Decrease in either fine or coarse grades.
	Subsequent loss from container.	Decrease in either fine or coarse grades.
PREPARATION	Unsound splitting method.	Increase in either fine or coarse grades.
	Faulty splitting practice.	Increase in either fine or coarse grades.
	Splitting to too small fraction.	Large errors in coarse grades.
	Loss of fine grades on cloth or from blowing.	Decrease in fine grades.
	Error in assumption that fine grades washed from aggregates are normal.	Probable decrease in finest grades with increase in intermediate.
ANALYSIS	Errors in sieve opening ratings.	Local errors between grades.
	Nonuniform sieve openings.	Local errors between grades.
	Incomplete shaking.	General increase in coarseness indicated
	Loss of fine grades by lodgement in sieves or elsewhere.	Decrease in finest grades.
	Errors in weighing.	Local large error, small general error.
Computation and Plotting	Errors due to use of slide rule.	Small local errors.
	Errors in plotting.	Small local errors.

There is another viewpoint in considering the accuracy of mechanical analyses. The means of interpreting mechanical analyses do not seem likely in the near future to reach an excellence capable of taking account of very small differences in mechanical composition. For purposes of interpretation the writer believes that errors in any grade amounting to less than 1/4 per cent of the whole sample times the square root of the percent of the grade (an arbitrary rule) may be regarded as negligible. Figure 2 shows the plotted pyramids for two analyses differing within this range. In a two-grade analysis if differences less than the amount stated are considered negligible there are still approximately 100 types of composition possible, disregarding those where one grade is less than 1 per cent. Similarly in a three-grade analysis there are approximately 5,000 types and in a four-grade analysis are well over 150,000 possible types of mechanical composition of which a large fraction would be likely to occur in natural sediments.

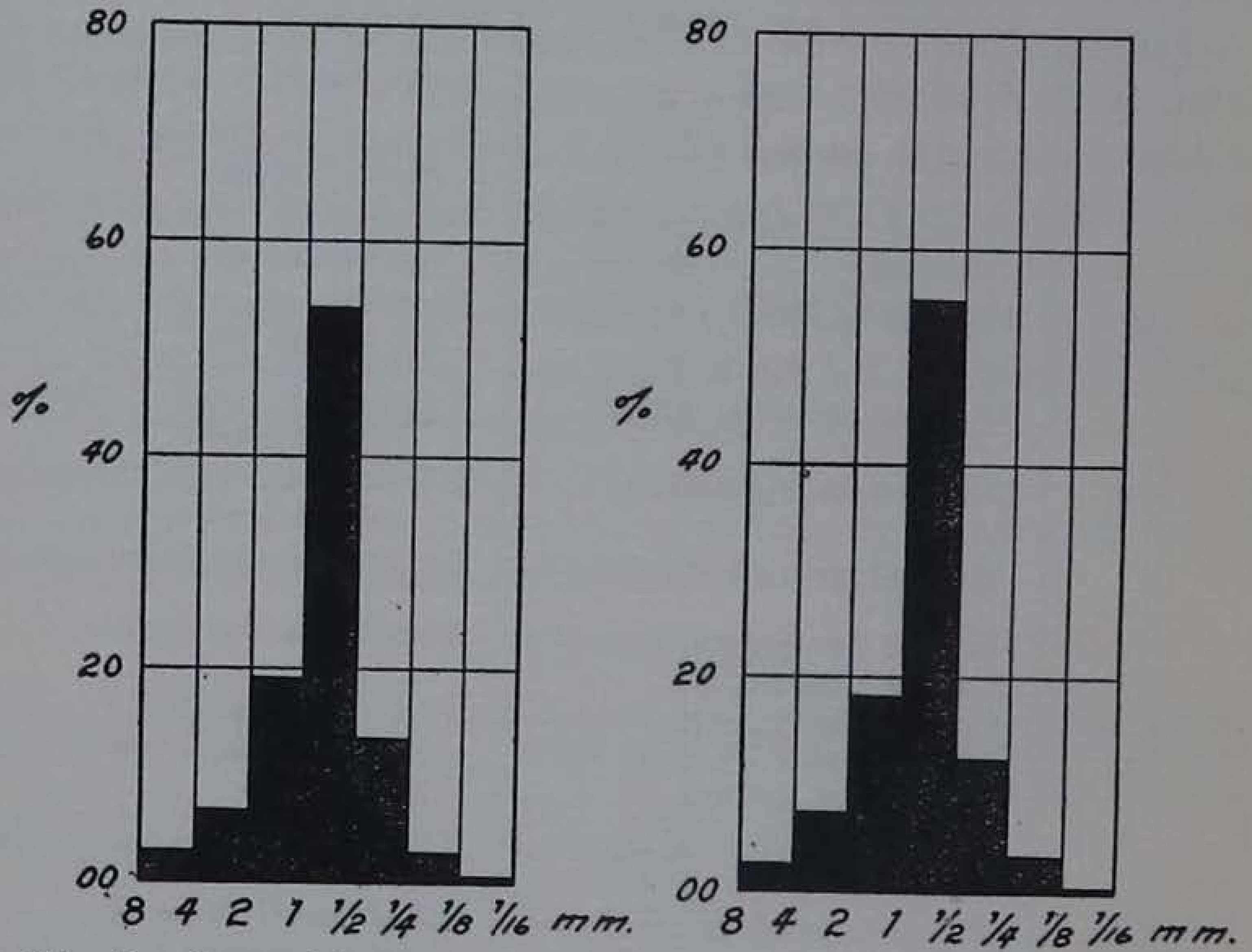

Fig. 2. Composition pyramids or histograms of two analyses differing by the limits described above.

The writer does not wish to advise against improvement of the accuracy of the sifting operation of mechanical analysis but he believes that the results at present attainable with reasonable care in the technique are so much in advance of the reliability of the collected samples and in advance of present methods of interpreting the analyses after they have been made that the principal emphasis in making for improvement should be placed at the two last named points. It seems, for example, that it would be much more profitable to collect and analyse in a fairly accurate and expeditious fashion 100 samples, computing the results by slide rule and presenting them in graphic form than to spend the same time on 25 samples, running analyses in duplicate, weighing to one more place of decimals and presenting the results to hundredths rather than tenths of a per cent.

ANALYSIS BY COUNTING

GENERAL STATEMENT

Under this heading are considered a number of methods which have in common the feature that the size of each fragment is determined by some sort of direct measurement. None of these methods may be considered preferable to the method of screening when the proper equipment for the latter is available and it can be applied, but are rather to be regarded as supplementary under exceptional conditions as applying to sediments beyond the range of screening.

ESTIMATING COMPOSITION IN THE OUTCROP

It is sometimes desirable to make an estimate of the relative abundance of boulders of different sizes in a coarse gravel or till and such is essentially an estimate of mechanical composition. It is sometimes possible to accomplish this by measuring the boulders in the reject pile of a commercial gravel pit where the large boulders encountered in working a known volume of gravel have been piled at one side to get them out of the way. More commonly such an estimate must be made from the outcrop and in such a case a large, fairly plane exposure normal to the bedding is most suitable. The procedure used by the writer is to select in the given outcrop a series of cobbles and boulders as reference sizes, one for each grade. These may be chosen to represent the mean size of the grade such as the series 90, 180, 360, 720, 1440 millimeters,[21] or the limiting sizes of 64, 128, 256, 512, 1024 millimeters. They should be chosen by actual measurement to conform as closely as possible to the square mesh sieve series. After marking these with chalk or otherwise the estimate should be made by standing well back from the outcrop and counting all those cobbles and boulders which appear to belong to each grade. In making use of such a count several principles should be borne in mind. First, the apparent size as protrud-

---

[21] Consisting of the series 64, 128, 256, etc. multiplied by $\sqrt{2}$ respectively.

ing from the outcrop is not the real size, being often smaller and in fewer instances (case of a broadside view of an elongate boulder), being larger. Second, the larger boulders which appear in the outcrop represent a much larger volume of the material than do the smaller cobbles which appear in the same outcrop. The first principle named probably does not introduce errors which would be regarded as large in an estimate of this kind since the general convexity of the exposed portion of the boulder will enable the observer on the average to place a given boulder in the correct grade even though the area exposed is much less than the true cross-section. The second principle must be considered more in detail. An adequate theoretical study of the relative probability of retention in the outcrop of large and of small boulders would be extremely complicated and the factors involved would have different values for a host of different rocks. For the present purpose it will suffice to eliminate a number of these by assuming a similar behavior for large and for small boulders. For example, any boulder may be said to be represented in the outcrop if, protruding sufficiently from the outcrop to be recognized as belonging to its proper grade, it is still well enough supported and held to remain in place. Similar retention in large and small boulders may be defined as the condition when the range of retention from a given percentage of linear protrusion needed for recognition to the larger percentage of linear protrusion when the boulder falls is a constant fraction of the average diameter of the boulder regardless of its absolute size. If this be the case then the boulders of several grades which are present in the outcrop represent volumes of material which stand in the ratio of the linear dimensions of the several grades. This approximate assumption will be made clear by reference to the following computation schedule.

In using this method of estimate the results obtained by methods so far described are relative and some absolute measure must be had to permit expression as a partial mechanical analysis. Perhaps the best method of securing this is by estimating the linear thickness of the zone of retention for one of the coarser grades by inspection. A grade in which there are a number of boulders should be used rather than to use very few boulders of extreme size. This measure times the length and height of the exposure will give the volume of which the number of boulders of the grade in question are a proper part and the volumes for the other grades are scaled from this, using the proportion principle stated above.

This method is, of course, not a quantitative one in the strict sense, yet it is believed that the present proper trend in geology is toward quantitative points of view and methods of expression and that estimates of this sort are of much value when undertaken by a competent observer who has the necessary theoretical principles in mind when making the observations and making the subsequent computation.

TABLE SHOWING REDUCTION OF FIELD DATA IN ANALYSIS BY COUNTING AT THE OUTCROP[22]

Grade sizes	Number of pieces	Number in unit volume	Total volume of grade[23]	Per cent of total
512-256 mm.	3	3	12188	7.4
256-128 mm.	18	36	18432	11.1
128- 64 mm.	29	112	7168	4.4
64- 32 mm.	15	120	960	.6
32- 16 mm.	21	336	336	.2
			39084	23.7

MEASUREMENTS OF THREE DIAMETERS

Measurements of three diameters are sometimes made in the course of studies of roundness or other shape characteristics and may be of subsequent value in separating the pebbles or cobbles into grades. In doing this the average diameter may be used for compact nearly equidimensional fragments, but use of the small cross-section (lesser times intermediate diameter) is more accurate for elongate forms.

---

[22] Values in column 3 are obtained from those in column 2 by multiplying by the multiples of 2 starting from the top, i.e., 1, 2, 4, etc. Column 4 is derived from column 3 by multiplying by cubes of the powers of 2; i.e., 1, 8, 64, 512, etc.

[23] Units are volumes of mean pieces of 32-16 mm. grade or

$$\frac{\overline{16\ (1.414)}^{\,3} \times 3.1416}{6} = 6{,}066 \text{ cu. mm.}$$

Unit volume is in this case an area of three square meters to a depth assumed as approximately the mean diameter of pieces of the larger grade; i.e., 35 cm. or practically 1/3 meter. The volume of the grades estimated is the product of 6,066 cu. mm. by the total of column four and is .237 cubic meters or 23.7 per cent of the whole. The cmoposition of the remaining 76.3 per cent must be determined by sieve analysis of a sample of the minus 16 mm. matrix.

ANALYSIS BY WEIGHT

The cobbles and pebbles of a coarse sample may be sorted into grades on the basis of weight fairly rapidly by using a spring balance and pan. After determining the grade limits by weight a paper scale having only three grade limits marked in strong lines may be attached to the face of the balance. Speed is increased by making a preliminary rough sorting by inspection, thus permitting the weighing of like sizes in close succession. If the range is great two or more balances of different capacities will be needed.

MICROSCOPIC COUNTING

The writer has had but limited experience in this type of mechanical analysis. Certain points in this limited experience seem worthy of mention. Counting is best done on a ruled surface or using a ruled eyepiece. For material over about 1/8 mm. paper ruled in millimeters has been used to good advantage as a background. Fine ruled gratings on glass for use on the microscope stage may be had of dealers in accessories. Eyepiece gratings have the disadvantage that they do not commonly conform to the grades used and if one is provided for use with one objective it will be of odd size if used with another. To get around various of these difficulties the following method is suggested. All microscope fields which are to be analysed are projected onto a frosted or ground glass surface above the microscope in the manner used for photomicrography. On this surface are drawn permanently the lines of a grating of appropriate size. By changing the distance of projection and the objectives it is practicable to enlarge grains of sediment of all grades to a standard image size and make all counts on the ground glass at this size, which can be large enough to greatly reduce eye fatigue. By the use of ordinary camera lenses as well as microscope objectives, all grades, even those which are readily estimated by direct inspection, may be projected to a standard image size, the larger fragments being reduced. Thus a whole sample may be subjected to the same technique and the inevitable break which would attend errors of judgment if the work were partly megascopic and partly microscopic is eliminated. Another advantage of this method is that the grains counted may be checked off on the ground glass with a pencil thus lightening the fatigue of sustained attention in ordinary microscopic counting.

ANALYSIS BY ELUTRIATION

Foreword

In the first outline of this paper it was intended that the analysis of fine sediments by elutriation should be treated at length. Progress of the work showed the inadvisability of attempting a detailed pretreatment at this time and the following brief outline is here presented as a supplement to the methods applicable to coarse sediments.

Outline of Methods

By some students the term elutriation is confined to separation of grains in a rising current apparatus, but by others it is also applied to separation by settling in a static column. The writer prefers the latter usage. Apparatus for elutriation has been described by a number of investigators and these descriptions need not be presented here. Four principal types may be recognized as follows:

1. Jars and cylinders for simple decantation.[24]
2. Simple tubes for rising current separation.[25]
3. Multiple tube series for rising current separation.[26]
4. Recording subsidence machines of the Oden type.[27]

Each type has points of merit. The simple decantation jars and cylinders are simple and easy to operate and with repeated washing results are as accurate as those derived by any other technique. Need for repeated washing is eliminated in the continuous current devices (2 and 3). In the Oden machine the true composition curve is deduced by mathematical analysis of the curve of settling. The continuous current devices have the disadvantage that the axial velocity and marginal velocity in the tube differ greatly and the exact conditions of separation at different temperatures are not known. The principal disadvantages of the Oden machine, as they appear to the writer, are the expense of construction and installation and the labor of computing results.

---

[24] Goldman, M. I., Petrography and Genesis of the Sediments of the Upper Cretaceous of Maryland, pp. 169-170, Baltimore, 1916.

[25] Holmes, A., Petrographic Methods and Calculations, p. 215, London, 1921.

[26] Holmes, A., *Op. cit.*, p. 209.
Hatch, F. H., & Rastall, R. H., Textbook of Petrology, The Sedimentary Rocks, pp. 342-357, London, 1913.
Cayeux, L., *Op. cit.*, pp. 36-45, 1916.

[27] Oden, Sven, Studien uber Tone, 2, Automatisch registrierbare Methode zur mechanischen Bodenanalyse, Bull. Geol. Inst. Univ. of Upsala, pp. 15-64, Upsala, 1919.

Grade Scales

All methods of elutriation involve the problem of hydraulic values of particles of varying size, shape and density at various temperatures. This problem has been approached by many investigators but no adequate determinations have been made of the effects of shapes of particles in modifying their velocity of fall through water.[28] Data given by different students show large variation.[29] Theoretical values, according to Stokes law, differ from any of the empirical values. Theoretical hydraulic values for spheres follow two different laws for large and for small particles. Large particles fall in water with velocities proportional to the square root of the diameter. Small particles fall with velocities proportional to the square of the diameter. (Stokes law.) Both rates depend on certain constants derived from the densities of water and the particle and the viscosity of water at the temperature in question. In the case of large particles viscosity is negligible; in that of small particles inertia becomes negligible. In the zone between 1.55 mm. and 0.2 mm.[30] for particles of the density of quartz both factors are important and the velocities undergo a transition from those of the square root law to those of the square law.[31]

In the case of a study of silts and clays in which the entire sample can be separated by elutriation, the grades may best be designated by the limiting falling velocities in millimeters per second, using a uniform ratio series like the powers of 2 or 3. The determined or supposed sizes of particles can be given as supplementary data. In many studies, however, the elutriation scale must be joined to the sieve scale and should have nearly the same size ratios between the grade limits as the latter. In his study of coastal plain gravels the writer used the following assumed hydraulic values for the continuation of the sieve grades:

---

[28] Richards, R. H., Textbook of Ore Dressing, p. 264, New York, 1909.

[29] Richards, R. H., *Op. cit.*, pp. 262-268.
Holmes, A., *Op. cit.*, p. 207.
Moles, E. C. Jul., Bulletin du Department de l' Agriculture aux Indes Neerlandaises, Buitenzorg, 1910, pp. 7-15.

[30] These values are given by Richards, *Op. cit.*, pp. 262-268, and by Holmes, *Op. cit.*, p. 206.

[31] This subject is briefly and cogently discussed by Richards, *Op. cit.*, pp. 262-268.

Diameter	Millimeters per second
1/16	4
1/32	4/3
1/64	4/9
1/128	4/27

This scale has no precise theoretical justification but is a simple and easily remembered scale closely approximating the mean of several published tables by hydraulic values throughout its range.

PROCEDURE

The general plan of elutriation by settling consists of allowing the particles to settle for a fixed period of time from a thoroughly mixed turbid suspension; at the end of that time the water and those particles not settled are drawn off as rapidly as possible with a syphon of glass or rubber tube. The settled portion is remixed with fresh water and the operation repeated. It is apparent that while all the larger particles are settling from the top of the column that a half of those particles which settle only half as rapidly will settle out of the lower part of the column; i.e., all of these contained in the lower half column. If the grade scale be built on the ratio 3 in hydraulic values instead of 2, the progress of separation by settling will be shown on the following table.

TABLE SHOWING PROGRESS OF REMOVAL OF FINER GRADES BY WASHING[32]

Grade limits mm. per second	Mean hydraulic value mm. per second	Per cent of grade present			
		After 1st. washing	After 2nd. washing	After 3rd washing	After 4th washing
27		100	100	100	100
	15.6	58	33	19	11
9		33	11	3.7	1.2
	15.2	19	3.7	.7	.1
3		11	1.2	.1	
	1.7	6.3	.4		
1		3.7	.1		

From the table it appears that after four washings of grade 81-27 mm. per second there will remain about 11 per cent of grains

---

[32] Time of settling just permitting grains of value 27 to fall from top.

of mean size in the 27-9 mm. per second grade, only 1.2 per cent of the smallest grains but approaching 100 per cent of the largest grains. It is evident that complete removal of grains just under the lower limit of the grade being washed is not practicable and some slight contamination by these remains even after many washings. In most work three or four washings must suffice. Corrections based on the principle of the table above may be applied if the need justifies and manipulations have been sufficiently precise.

In the rising current type of elutriation a few minutes of operation will do the work of many washings, but here also the removal of grains just below the lower size limit of the grading being washed is relatively slow. The writer is not aware that rising current elutriations have been devised for very low velocities, such as those below 1/50 mm. per second except as attempted in the Yoder centrifugal elutriator.

DEFLOCCULATION[33]

In analysing clays, important difficulties arise because of the presence of materials having colloidal properties and capable of forming aggregates under varying electrolytic conditions. In all analyses by elutriation it is desirable to use distilled water and reduce error due to flocculation to as low a value as possible. Water from condensed steam in a heating system or rain water is preferable to tap water where distilled water in the necessary quantities is not available. In analysing most clays treatment for deflocculation is necessary. For a description of methods the reader is referred to the work of Goldman,[34] Milner,[35] and Steiger.[36]

Clays differ so widely one from another that it is difficult to give precise directions applicable to all. Probably the best general procedure is a deflocculation by shaking in a solution of sodium carbonate or ammonia and suspension for elutriation in a similar weakly alkaline solution. It is to be borne in mind that electrical energy must be supplied to bring about the electrical neutralization of the

---

[33] In writing and revising this section the writer has had the benefit of valuable suggestions and advice from M. S. Littlefield, of the University of Iowa, M. I. Goldman, of the U. S. Geol. Survey, and R. O. E. Davis, of the U. S. Bureau of Soils.

[34] Goldman, M. I., The Petrography and Genesis of the Sediments of the Upper Cretaceous of Maryland, pp. 115-119, Johns Hopkins Univ. Press, 1916.

[35] Milner, H. B., An Introduction to Sedimentary Petrography, p. 24, London, 1922.

[36] Steiger, Geo., Treatise on Sedimentation, Edited by W. H. Twenhofel, pp. 630-631, Baltimore, 1926. See also U. S. Bureau of Soils, Bulletins 24 and 84.

aggregated clay particles and effect deflocculation, and also that though the sizes of the aggregates may be materially reduced by such treatment complete deflocculation such that each subsiding particle is a single mineral grain is essentially impossible except by a precise treatment worked out by the student with particular reference to the physical and chemical condition of the sample in hand.

It is further necessary to emphasize that since all natural clays consist largely of colloidal material in varying degrees of flocculation and were such at the time of accumulation, it is futile to hope in most cases that conditions closely approaching those obtaining at the time of deposition can be set up by treatment for deflocculation or that the size distribution as determined by hydraulic methods can be used in the interpretation of the aqueous conditions of origin with confidence in those sediments fine enough to be materially affected by colloidal phenomena. The writer does not wish to convey the idea that it is useless to attempt to analyse fine grained sediments, but he does wish to emphasize the view that results obtained by a routine application of any single procedure to a variety of sediments are not likely to be of great significance or value in interpreting the origin of the material in question. It should be borne in mind that some sediments may have been in a highly flocculated condition at the time of deposition and that to attempt complete deflocculation as a general goal is as pernicious as the analysis of sediments without any deflocculation procedure.[37] It is to be hoped rather that each student will endeavor, by a study of the behavior of the sediment in hand under various electrolytic conditions and by a study of resulting particles under the microscope, to learn the nature of the existing state of aggregation and to adapt his treatment for deflocculation so as to convert the sediment most nearly into a significant previous condition of aggregation whether that requires complete deflocculation, or very little, or none at all.

COMPUTING AND PLOTTING

Methods of Computing

The computing involved in mechanical analysis consists for the most part of simple percentage arithmetic. For most purposes it can be carried out with sufficient accuracy by means of a ten-inch slide rule. When a sample has been analysed in one stage it is com-

---

[37] Davis, R. O. E., The Interpretation of Mechanical Analysis of Soils as affected by Soil Colloids, Jour. Amer. Soc. Agronomy, Vol. 14, pp. 296-297, 1922.

monly the case that the total of the separate weights is slightly less than the weight of the total sample before analysis. With reasonable care the discrepancy can be kept down to a fraction of one per cent, even on light samples of but a few grams. The loss may be from any of the grades by lodgement in the sieves or otherwise. It is the custom among some workers to consider that the entire loss is from the fine grade. Unless this has been proven to be the case by careful tests, it seems better as a general practice to distribute the error among all the grades. This is accomplished by using the total resulting by addition of the separate weights rather than the original one.

In computing the percentages by slide rule slight errors of manipulation and reading will enter, causing the total of the percentages to add to less or more than 100. Here the discrepancy need be no more than one or two tenths of one per cent and it is the writer's custom to compute the largest percentage last and by adding the column of tenths of the other percentages determine the proper digit to be read in the tenths of the last and largest percentage. This should rarely differ from that actually appearing on the rule by more than .2 per cent. The result is then set down and checked by addition of the total to 100 per cent. Arithmetic or logarithmic methods can be applied similarly. The schedule given below is for the purpose of making more clear the methods of computing and also to summarize the procedure of one of the more complicated multi-stage analyses.

Total weight of sample = 13.79 kg.

Sieve grades	Weight	
+64 mm., separate washed	1.32 kg.	
+32 " " "	2.61 "	
+16 " " "	1.76 "	
Total	5.69 kg.	13.79 kg.
		5.69 "

—16 m., total weight (Too sticky for sifting) 8.10 kg.

Dried, mixed, quartered down

total weight used 4.17 kg.

Small quantity shaken over 1/16 mm. sieve to secure about 10 grams of normal —1/16 grade. Rest returned and total of close to 4.17 grams washed in jar with hose to take out bulk of —1/32 grades. Residue then dried and sifted.

Sieve grades	Weight
+8 mm. separate	.73 kg.
+4 " "	.54 "
+2 " "	.48 "
Total	1.75 kg.

Weight
4.16 total –16 mm.
1.75 total 16-2 mm.

Total —2 grade 2.42 kg.

This residue of 2.42 kg. was quartered down to 47.31 grams and sifted.

Sieve grades	Weight
+1. mm., separate	10.31 gm.
+1/2 " "	11.73 "
+1/4 " "	6.30 "
+1/8 " "	4.29 "
+1/16 " "	3.89 "
	36.52 gm.

47.31 gm. total –2 mm.
36.52 " " 2-1/16 mm.

10.79 gm. total –1/16 mm.

Then –1/16 remaining is less than the total amount by amount of that washed out. Some of the material originally saved from the –16 grade above is used for the elutriation.

Settling grades.

4/3 mm. per sec. separate	1.83 gm.
4/9 " " " "	1.64 "
4/27 " " " "	.89 "
–4/27 " " " "	.15 "
Total	4.15 gm.

Computation usually performed by slide rule.

Total sample of 13.79 kg.	= 100%	
then +64 " of 1.32 "		= 9.6%
+32 " of 2.61 "		= 18.9%
+16 " of 1.76 "		= 12.8%
-16 " of 8.10 "	= 58.7%	
Total -16 " of 4.17 "	= 58.7%	
then +8 " of .73 "		= 10.3%
+4 " of .54 "		= 7.6%
+2 " of .48 "		= 6.8%
-2 " of 2.42 "	= 34.0%	
Total -2 " of 47.31 gm.	= 34.0%	
then +1 " of 10.31 "		= 7.4%
+1/2 " of 11.73 "		= 8.4%
+1/4 " of 6.30 "		= 4.5%
+1/8 " of 4.29 "		= .13%
+1/16 " of 3.89 "		= 2.8%
-1/16 " of 10.79 "	= 7.8%	
Total -1/16 sample of 4.51 gm.	= 7.8%	
then +4/3 mm. sec. sample of 1.83 gm.		= 3.2%
+4/9 " " " of 1.64 "		= 2.8%
+4/27 " " " of .89 "		= 1.5%
-4/27 " " " of .15 "		= .3%
	Check	100.0%

Choice of Plotting Scales

When the grade scale has been decided upon and the analyses made and computed there still remain a variety of forms in which the results may be presented. If a graphic form is chosen, whether pyramidal or cumulative as described below, choice must be made in either case whether the coarse grades shall be at the left or at the right of the diagram and what ratio shall obtain between the vertical percentage scale and the horizontal grade scale. A large number of different conventions have been used in the past with the result that direct comparison between the results obtained by different students has been impossible.[38] The great diversity which can be developed

---

[38] Goldman, M. I., Petrography and Genesis of the Sediments of the Upper Cretaceous of Maryland, pp. 169-170, Baltimore, 1916.

Woodford, A. O., The San Onofre Breccia, Univ. of Calif., Publications, Bull. of the Dept. of Geol. Sciences, Vol. 15, No. 7, p. 175, 1925.

Holmes, A., Petrographic Methods and Calculations, pp. 217-225, London, 1921.

(Footnote continued on page 48)

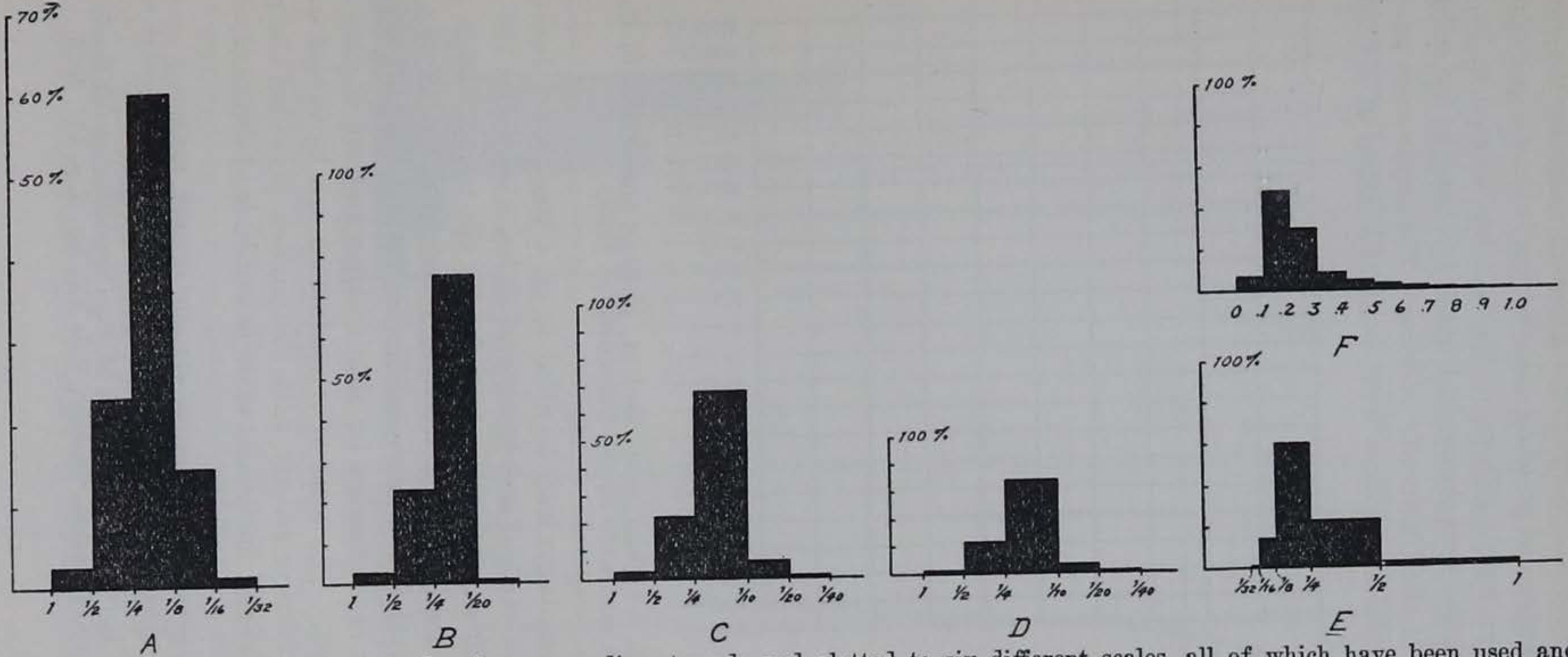

Fig. 3. Composition histograms for the same sediment made and plotted to six different scales, all of which have been used and published. The variation beyond the limits of recognition is apparent.

in the composition diagram of a given sediment by the use of different grade scales and plotting conventions is shown in Figure 3. Plotting with the coarse grades at the left has seemed to be most convenient and the card shown in Figure 4 is used in the sedimentation laboratory at the University of Iowa. The grade scale spaces on this card are made to conform with vertical spacing of a typewriter so that the percentages may be filled in on a machine if desired. The ratio between vertical and horizontal scales is such that 100 per cent is equal to 20 grades of the ratio 2. By the use of such a card for plotting all analyses as a laboratory record the diagrams are immediately available in any combination or arrangement without redrawing for reproduction by zinc etching and much time is saved in publication. The scale of reproduction can be varied somewhat without interfering greatly with comparison provided the ratio between vertical and horizontal scale is maintained constant.

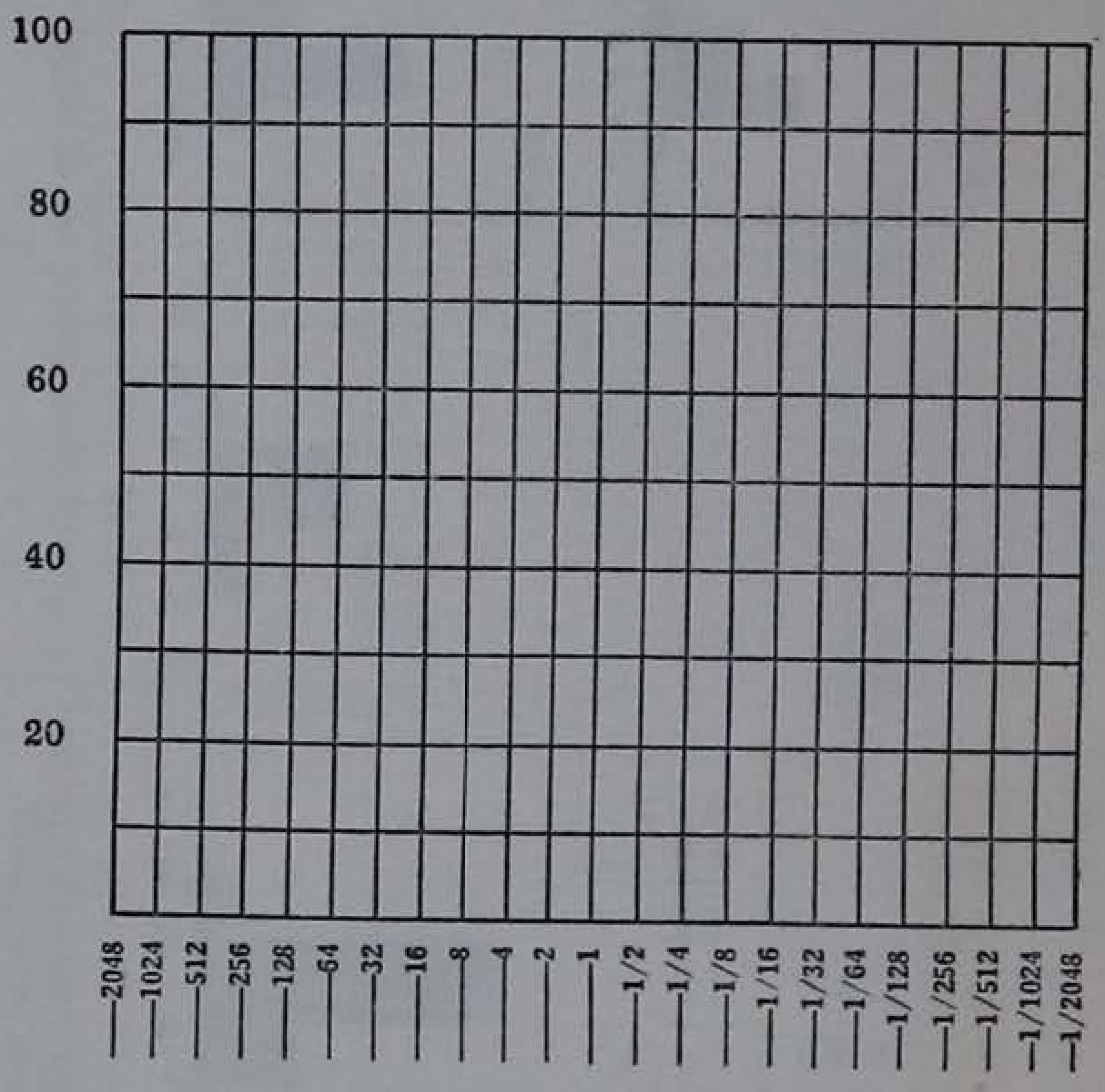

Fig. 4. Form card used in plotting histograms to the 1-2-4-8 mm. scale at the University of Iowa.

Baker, H. A., Geol. Magazine, pp. 411-420, 463-467, 1920.

Dake, C. L., The Problem of the St. Peter Sandstone, Missouri School of Mines Bulletin, Vol. VI, No. 1, Plates V-XII, incl., 1921.

Trowbridge, A. C., and Mortimore, M. E., Correlation of Oil Sands of Sedimentary Analysis, Economic Geology, Vol. XX, No. 5, p. 417, 1925.

Distribution and Cumulative Diagrams

Two types of diagrams are in current use and both have good claims for recognition. The distribution pyramid shown in Figure 5 has the advantage that it is a strict presentation of numerical facts.

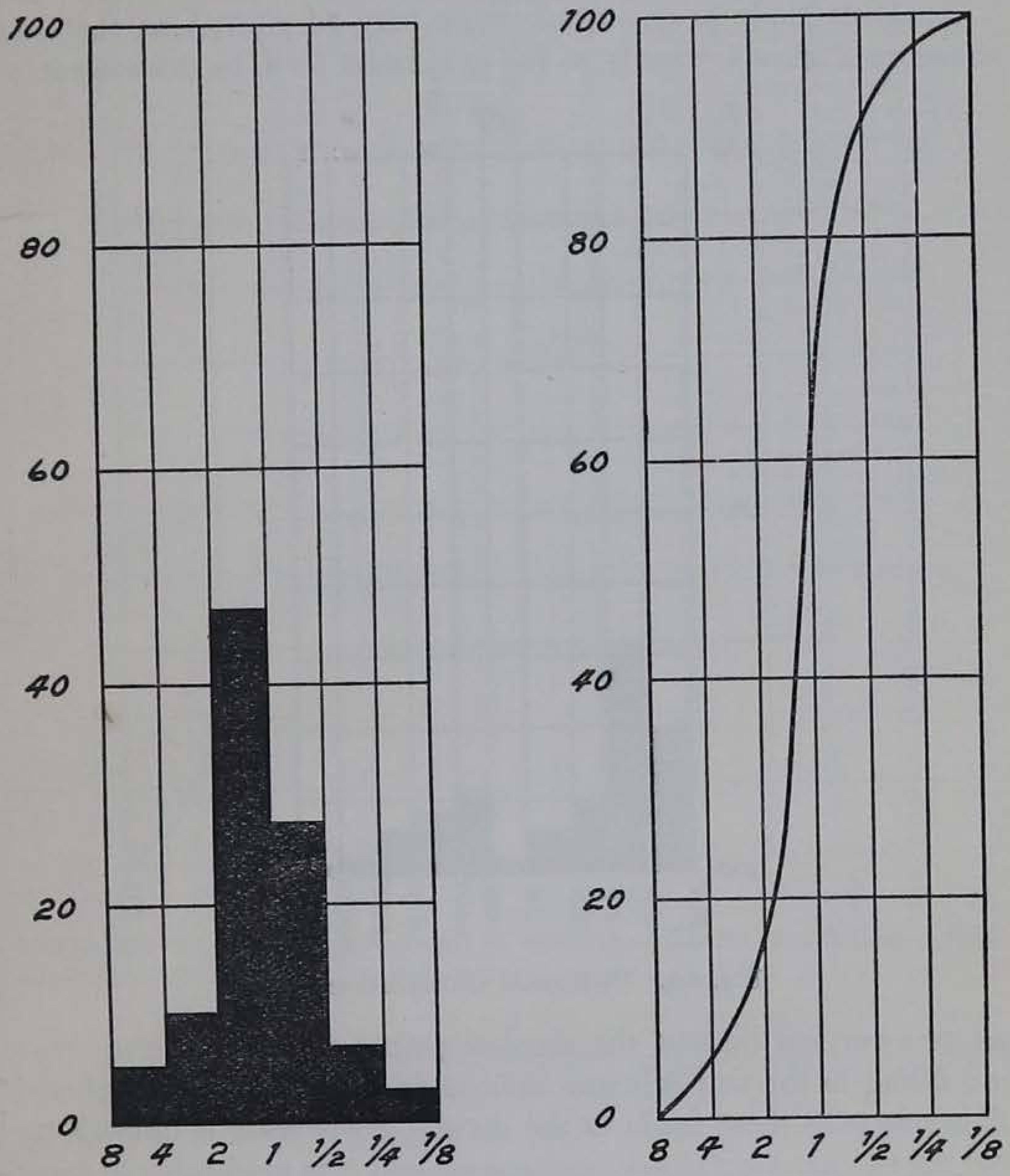

Fig. 5. Histogram and cumulative curve for the same composition.

There is no element of interpretation in it. It is probably more readily visualized by persons unaccustomed to either than is the cumulative diagram. The latter diagram is partially interpretative in the drawing of the smoothed curve and permits the presentation of several diagrams in one plot. It also permits the plotting of analyses made to different grade scales on the same diagram more readily. It seems that each type of scale has its own advantages and that both may sometimes be needed to convey most effectively this type of data.

TRANSFORMATION OF GRADE SCALES

Analyses made to any grade scale may be plotted on the cards shown in Figure 4 directly in the pyramidal form by drawing intermediate vertical lines at the abscissæ points of the new grade scale and filling in the new columns thus made. The comparison of such diagrams with those made to the normal grade scale is difficult unless the two are very closely juxtaposed and it is preferable to transform the analysis in question to the standard grade scale. This is done by plotting the analysis in the cumulative form and drawing a smooth curve through the fixed points. Ordinates may now be read on the curve for the abscissae points of the standard grade scale and the pyramid plotted for these values as read. (Figure 6.) Similar methods may be used for constructing a pyramidal diagram of smaller grade ratios, Figure 6-D. No more information is added

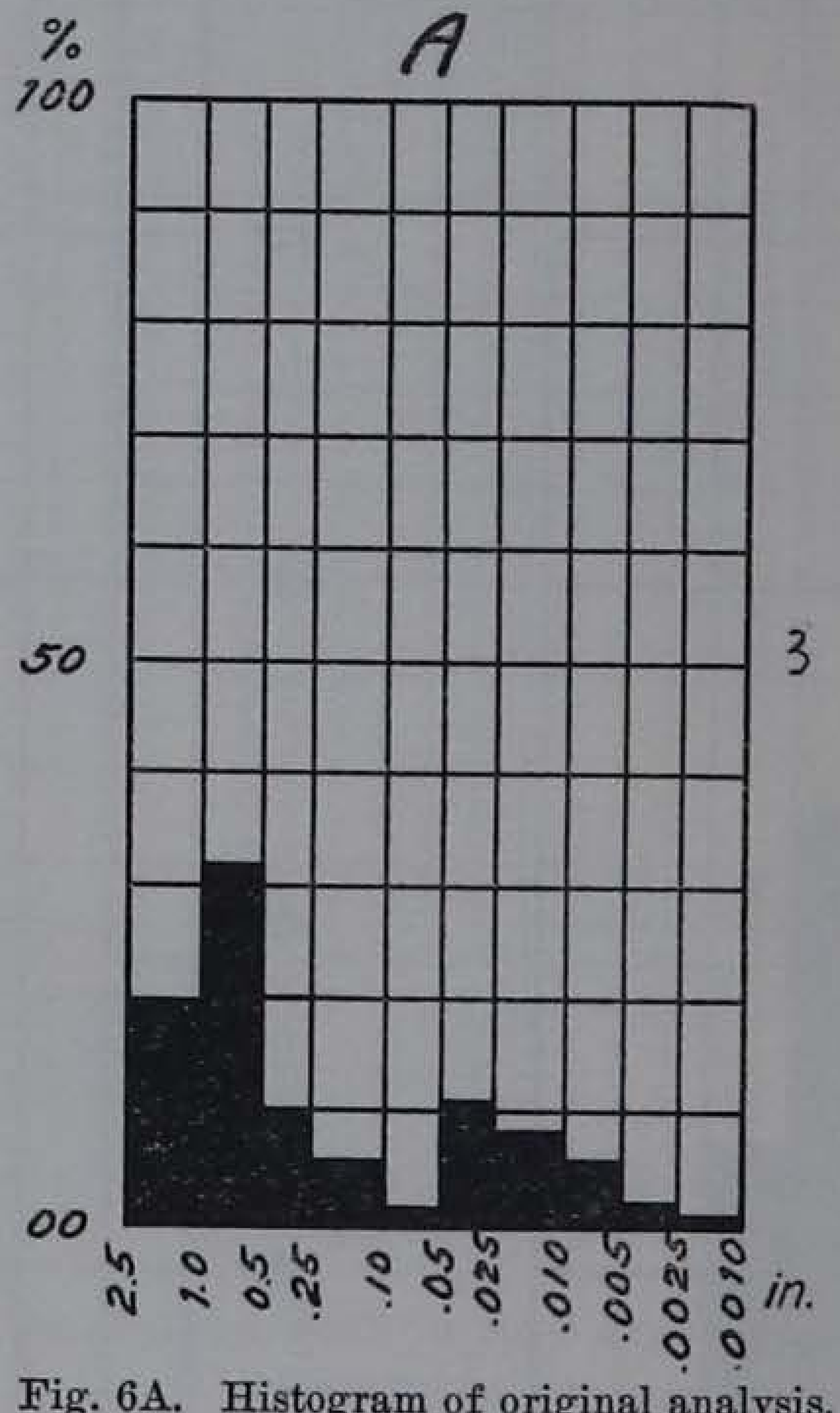

Fig. 6A. Histogram of original analysis.

in such transformation and the result is slightly less accurate than the fundamental pyramid of the grade scale of analysis but the form may be more favorable for interpretation.[39]

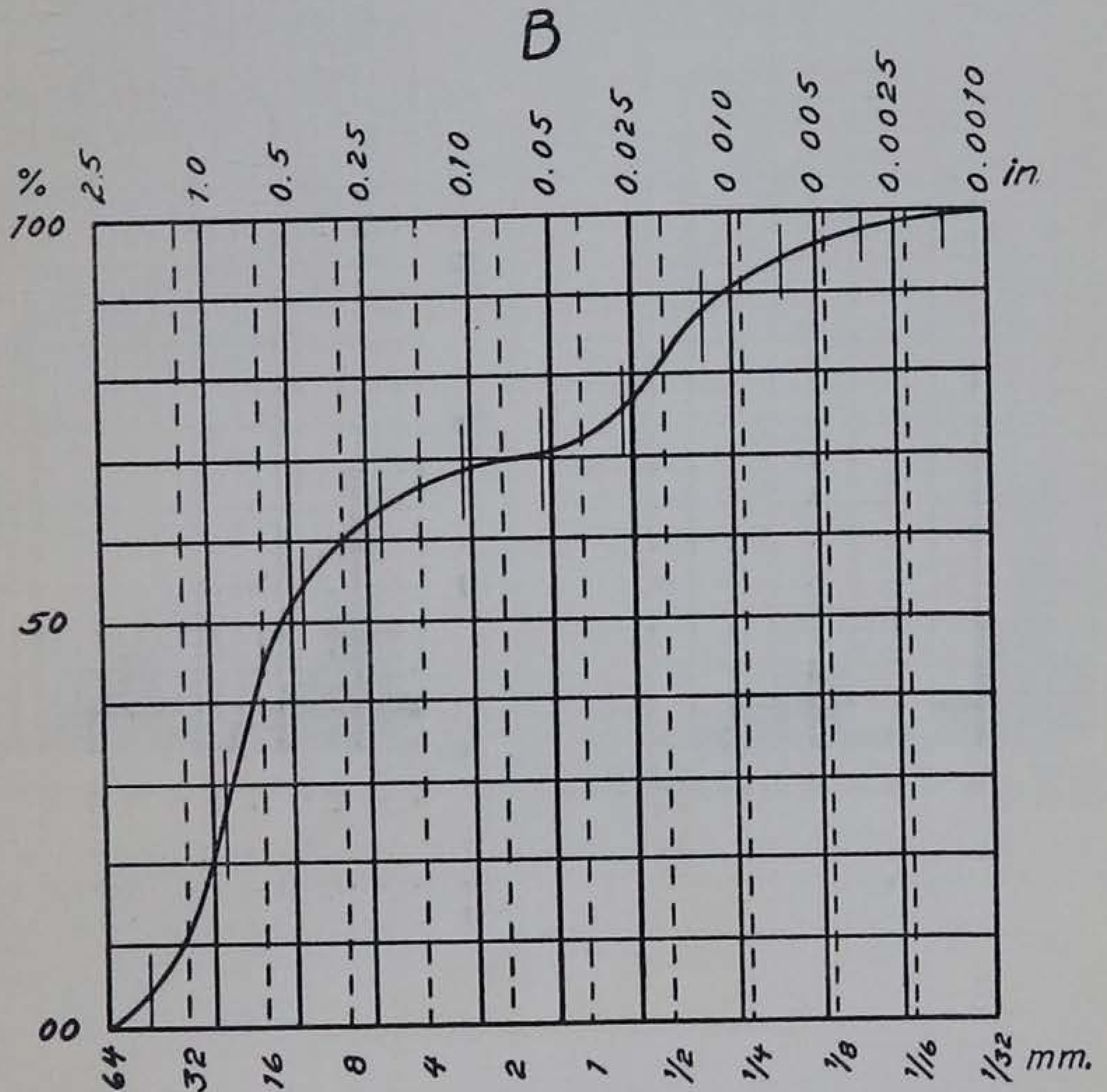

Fig. 6B. Cumulative curve used in reading ordinates at abscissæ points of desired scales.

---

[39] This paper is to be followed by another consisting of a graphic compilation of several hundred mechanical compositions of modern sediments for comparison and reference.

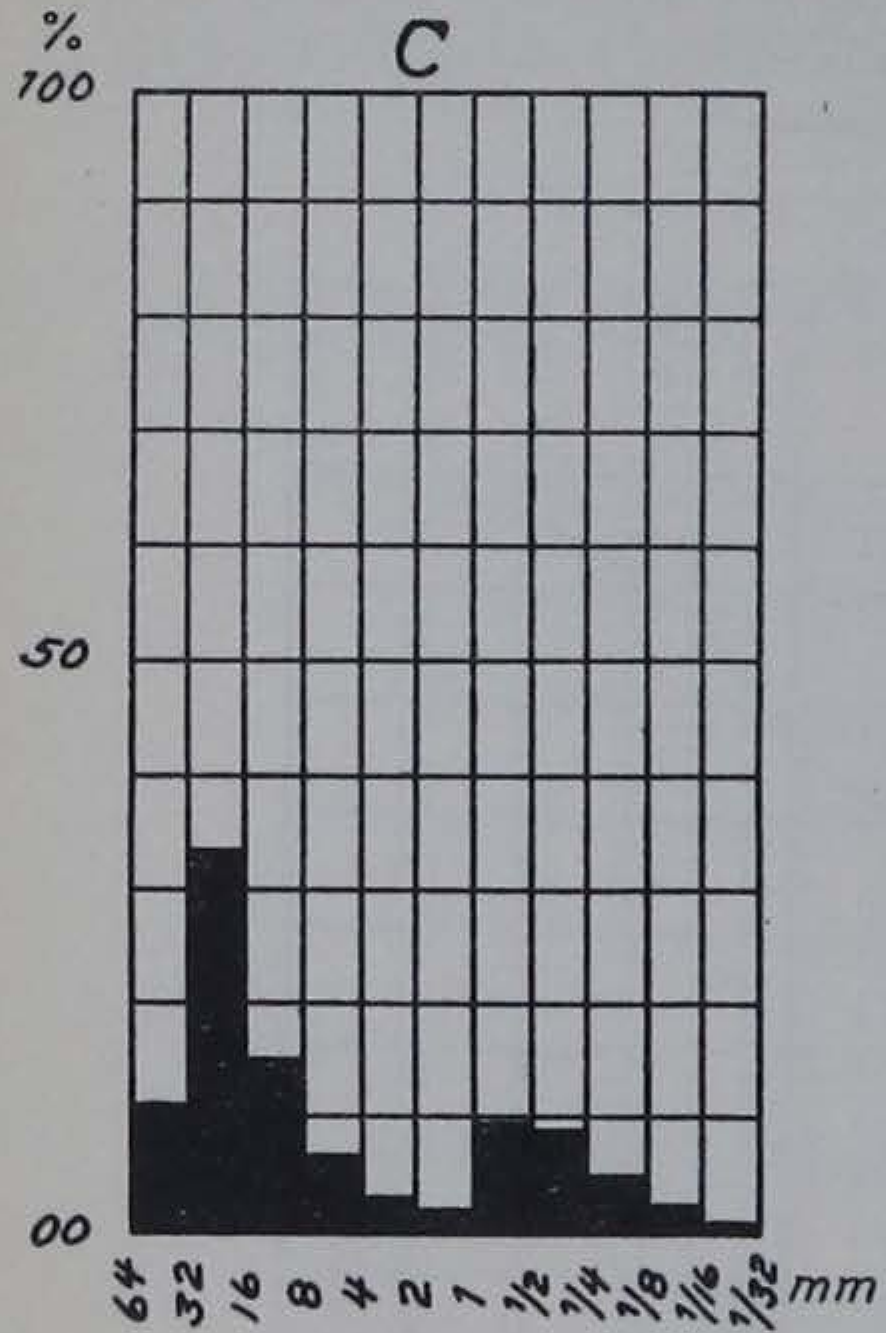

Fig. 6C. Histogram of same data transformed 1-2-4-8 mm. scale.

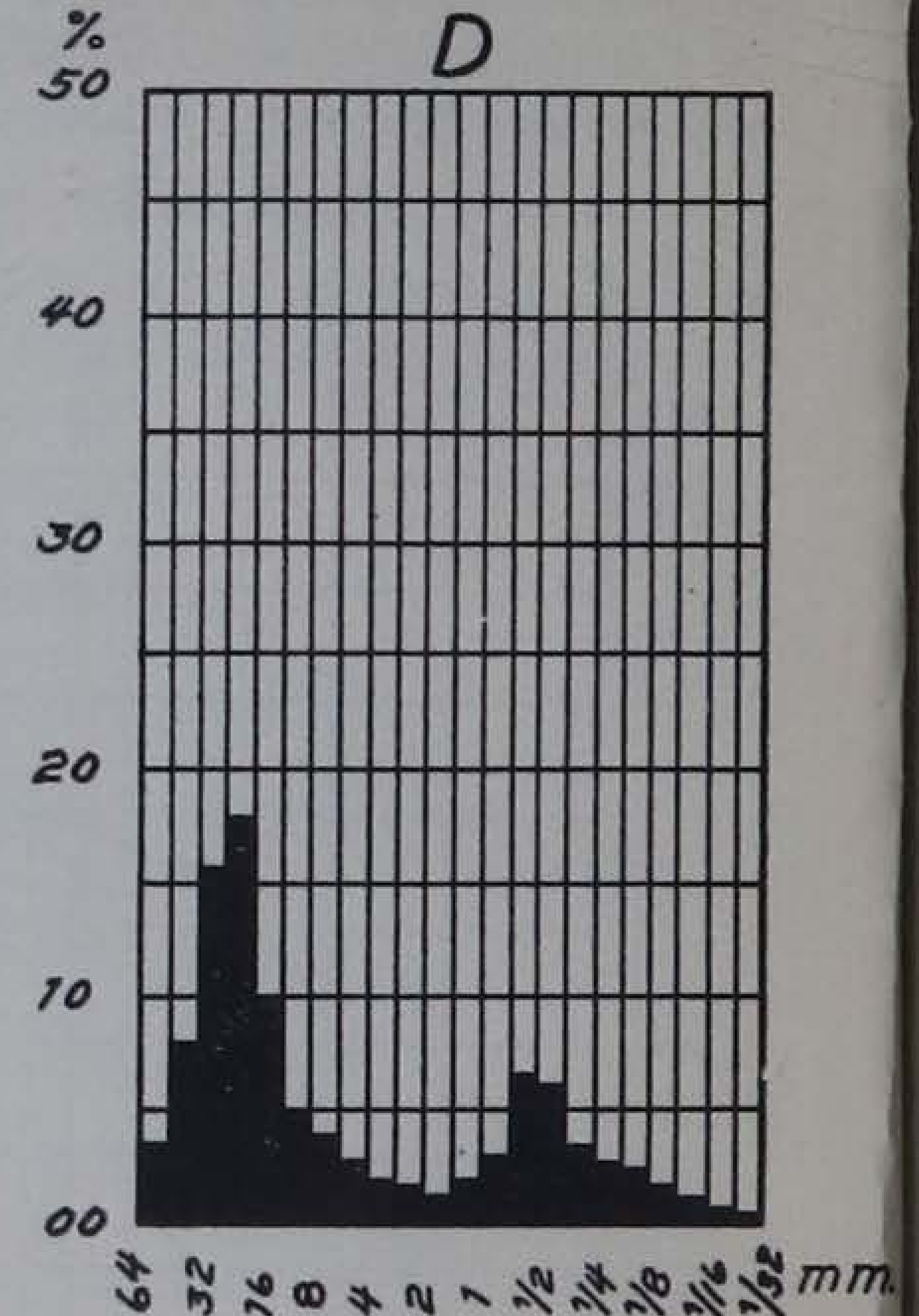

Fig. 6D. The same plotted to twice the number of grades, *i.e.*, ratio of the square root of 2.