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THESIS

This is to certify that the

thesis entitled

*A Petrographic Investigation of
the Longitudinal Deposition within
the Mason Esten relative to its
Origin.*

presented by

Ralph LeRoy Erickson

has been accepted towards fulfillment
of the requirements for

M.S. degree in *Geology*

Stanard G. Bergquist
Major professor

Date *Dec., 10th, 1948.*

**A PETROGRAPHICAL INVESTIGATION
OF THE LONGITUDINAL DEPOSITION WITHIN THE
MASON ESKER RELATIVE TO ITS ORIGIN**

**By
Ralph LeRoy Erickson**

A THESIS

**Submitted to the School of Graduate Studies of Michigan
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for the degree of
MASTER OF SCIENCE**

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INTRODUCTION

One of the most interesting glacial deposits is the esker, a long narrow ice-contact ridge commonly sinuous, and composed chiefly of stratified drift.

Eskers range from a few feet to more than a hundred feet in height, from twenty to several hundred feet in width, and from a fraction of a mile to nearly 150 miles in length. The sides are generally steep; the crests are smooth.

The origin of eskers has been a controversial subject since they were first recognized as glacial deposits. William M. Davis*

*Davis, William M., The Subglacial Origin of Certain Eskers: Boston Society of Natural History, Proceedings, vol 25, pp 477-499, 1893.

believed that eskers were sub-glacial channel deposits. His explanation presumed a stagnant and decayed marginal zone of the ice sheet. Water resulting from the basal melting of the ice, together with water from surface melting, which becomes subglacial through the medium of crevasses, is gathered into streams. Considerable detrital material is picked up by these streams. Should these subglacial streams become overloaded, a certain amount of detrital material will be deposited. If the stream is diverted, the deposit will be left in the abandoned tunnel and gradually will develop the steep lateral slopes and other formal features of eskers during the

slow melting of the retaining ice walls.

In 1893, Warren Upham*

*Upham, Warren, Evidences of the Derivation of the Kames, Eskers, and Moraines of the North American Icesheet Chiefly from its Englacial Drift: Geological Society of America, Bulletin, vol 5, pp 71-86, 1894.

supported the englacial theory of drift transportation and deposition. He believed that the drift was not carried forward beneath the ice, being pushed or dragged along in contact with the land, but that the drift was carried within the ice in the lower part of the ice sheet. Such a hypothesis states that as the glacier thins the deposited sediments are gradually lowered to the ground.

W. O. Crosby*

*Crosby, W.O., The Origin of Eskers: Boston Society of Natural History, Proceedings, vol 30, pp375-411, 1902.

opposed Davis's subglacial channel theory, and proposed the superglacial stream theory, whereby the sand and gravel were deposited in streams flowing on the surface of the glacier and later lowered to the ground in the same manner as the englacial theory above.

A.D. Trowbridge*

*Trowbridge, A.D., The Formation of Eskers: Science, new series, vol 40. p 145, 1914, abstract.

suggested that eskers were formed by slow recession of the edges of glaciers during the deposition of kames and resulted in the drawing out of the kames into serpentine-like ridges. This would mean headward building of the esker in successive segments, each marked by a delta where the esker stream entered a glacial lake.

Richard F. Flint*

*Flint, Richard F., American Journal of Science, 5th series, vol 15, pp 410-416, 1928.

advanced still another possibility: that several glacial deposits which have been described as eskers are actually crevasse fillings and are less closely associated with eskers than with marginal lake and outwash deposits.

It is probable that eskers are formed in several distinct ways and places: in subglacial channels, in superglacial channels, in englacial channels, headward building of successive kames, and crevasse fillings, all with or without the active agency of water. All these theories are no~~x~~ doubt essential to a complete explanation of eskers.

LOCATION

The Mason esker is one of the longest observed in Michigan and is approximately twenty miles in length. It extends from the gravel pit at the corner of Main and Shepard streets in Lansing, southeast through Mason, the county seat of Ingham County, and has its southern terminus in

the Charlotte morainic system southeast of Mason (Fig 1).

PURPOSE OF THE STUDY

The purpose of this paper is to illustrate the value of a detailed petrographic study of the esker sand as an aid in determining the origin of a particular esker. This study is based upon seven field samples taken from the Mason esker at two- or three-mile intervals.

METHOD OF INVESTIGATION

General.

A detailed petrographic study of any sand involves frequency counts of heavy minerals and roundness and sphericity measurements of quartz grains. Most sand is composed chiefly of quartz; therefore the quartz grains may not serve as a key mineral in the identification or recognition of a particular sand. However, most samples contain several minor constituents which have a high specific gravity. These minerals may be amphiboles, pyroxenes, garnets, zircons, titanite, etc. If, in some manner, these heavy minerals can be separated from the quartz grains, identified and counted, they may serve as a factor in the correlation and recognition of esker sand.

Roundness and sphericity are two fundamental properties of sedimentary particles, and are the most recent to be studied quantitatively and statistically. Early observers noted the modification of shape that took place by transportation.

F. J. Pettijohn*

*Pettijohn, F. J., Manual of Sedimentary Petrography, D. Appleton Century Company, p 278, New York, 1938.

states that the factors that control sphericity and roundness are: (1) the original shape of the fragment, (2) the structure of the fragment, as cleavage or bedding, (3) the durability of the material, (4) the nature of the geologic agent, (5) the nature of the action to which the fragment is subject and the violence of the action, and (6) the time or distance through which the action is extended. If a roundness and sphericity value can be obtained for quartz grains of a particular deposit, this value would serve as a correlation possibility with other deposits.

This study, therefore, is concerned with the comparison of the heavy mineral suites and the roundness and sphericity values of quartz at the seven stations studied in the Mason esker.

Field Sampling.

The seven sample stations along the Mason esker were chosen not at regularly spaced intervals but wherever commercial gravel companys had cafried on operations. These gravel pits presented a good vertical face through the center of the esker and permitted an accurate sand sample to be obtained from top to bottom.

Extreme caution had to be exercised in order to insure

an equal concentration of sand from each horizon. A channeling method was used whereby vertical channels were drawn downward and the sediment dislodged was caught in a scoop. The sand from each channeling operation was collected in a bucket. After collecting a complete sample from top to bottom of the esker, a Jones sample splitter was used. For the purpose of this study an 800 gram sample was retained from each station.

Laboratory Sampling.

Since these seven field samples consisted of unconsolidated sand and gravel, no disaggregation problems were encountered and the analysis was begun as soon as a test sample of approximately 400 grams had been split from the field sample. The sand was poured into an ordinary quart jar, filled with water and the mud removed by decantation. In view of the fact that this is a petrographic study of esker sands, the presence of mud would have been objectionable.

Leaching.

After the washed sand had been thoroughly dried, 200 grams of each sample was retained. A 10% HCl solution was added to each of these samples to remove all carbonates which also are an objectionable inclusion in a petrographic study. This process was repeated until no more reaction was visible. In order to give some idea of the concentration of carbonates in each of the seven samples, the resi-

due was carefully weighed and the results plotted in graph form (Fig. 2). These percentages are of little importance however, insofar as the homogeneity or heterogeneity of the mineral suites are concerned, since the carbonates are largely secondary in origin. The graph simply shows that carbonates were present at all stations and in roughly the same concentration.

Sieving.

After leaching and drying, the residues were placed in a Ro-Tap sieving machine for a 15 minute period. Six sieves were used in the Ro-Tap: 48, 65, 100, 150, 200 meshes per inch. Each sieve size was weighed to the nearest milligram. A graph comparing weight percentages of the sieve sizes at all stations is shown in Fig. 3. The sieving was done primarily to separate the sample into convenient size units for further study, and not as an instrument of mechanical analysis. The theory of sieving involves a number of complexities which limit the accuracy of the operation. E. A. Mitschlerlich*

Mitschlerlich, E. A., *Bodenkunde für Land-und Forstwirte*, Berlin, 1905, p 37.

pointed out a number of years ago that sieving sorts grains not only according to size but also to shape. This might be illustrated by considering lath-shaped and spherical grains. The largest sphere that can pass through a given

mesh is a sphere with a diameter equal to that of the mesh, whereas a lath-shaped grain with such a diameter and any length could pass through the sieve. This naturally would allow for a great differential in volumes of the grains. Therefore sieving is not truly a size analysis.

Despite the validity of the above criticism, sieving is still a widely accepted practice and does have a purpose. The criticism is included primarily as a warning to those who read the graph not to interpret it with a view towards homogeneity or heterogeneity of the test stations.

The Mason esker is crossbedded and stratified with coarse gravel lenses pinching in and out and highly suggestive of stream deposits. A sample taken from one gravel pit which contains mostly fine sand would not be expected to have the same size frequency as the sample taken from the pit with many coarse gravel lenses.

The sieving separated the samples into convenient size units for the most vital and important study of this problem; the heavy mineral frequency counts and the roundness and sphericity measurements of quartz grains.

Separation.

The separation of the heavy minerals from the light was accomplished by means of bromoform, a gravity separation, in which the heavy minerals sink and collect while the light minerals such as quartz and feldspar will float. One gram of each of the first three sieve sizes (20-48,

48-65, 65-100) and 500 milligrams of the last three sieve sizes (100-150, 150-200, 200 plus) for each of the stations in the esker were weighed. It was discovered by trial and error that this amount could be easily separated and still provide enough heavy minerals to study. In order to eliminate as much error as possible, each sieve size was quartered by pouring the sample into a conical pile on a sheet of paper and separating the sand into four quarters by cutting it along two diameters. Alternate quarters were retained and combined and the process repeated until approximately one gram or 500 milligrams remained.

Bromoform (tribrom-methane) was used as the separating agent. Bromoform has a specific gravity of 2.89 at 10 degrees Centigrade. This is sufficient to separate quartz and feldspar from the heavier minerals. Commercial bromoform has a low specific gravity because of dissolved alcohol. The specific gravity was increased by adding water and decanting the alcohol-water phase. After decantation, the bromoform-water mixture was poured into a separating funnel, drawn off, and passed through several thicknesses of filter-paper which absorbed the dispersed water.

The separation apparatus consisted of a filtering funnel with a short length of rubber tubing and a pinch-cock fitted to the stem. The funnel should be as broad as possible so that the floating minerals may spread over the heavy liquid. The grains may be agitated to overcome any tendency to "ball up". A second funnel with a filter paper

was placed below the first. A beaker under the second funnel caught the filtrate. The funnels should be constructed to remove easily the heavy mineral concentrate and they should not be so constricted that clogging occurs. A watch glass was placed over the funnel to reduce evaporation.

After separation, the heavy minerals were allowed to flow into the lower funnel and were caught on filter paper. The heavy minerals were washed with alcohol to remove the bromoform. After the heavy minerals had been removed a new filter paper was inserted in the lower funnel. This paper caught the light minerals as the bromoform was allowed to flow through the funnel.

The heavy and light minerals of the six sieve sizes for each station were separated simultaneously with a battery of six separation units.

The "lights" and "heavies" were each weighed and the "lights" put into vials and labeled. A small horseshoe magnet removed all the magnetite from the "heavies". The magnetite was removed in order to facilitate the heavy mineral frequency count.

Mounting for Microscopic Study.

A representative fraction of the minerals to be used for mounting must be chosen with care. Quartering was again necessary. The writer used the method suggested by

Pettijohn*,

*Pettijohn, F.J., Op. Cit., p 357.

in which four rectangular sheets of paper, 2x4 inches, were placed together in such a manner that each overlaps one half of the other, and altogether form a square. The minerals, heavy or light, were poured into the center of the square. The pieces of paper were pulled apart, alternate quarters rejected, alternate quarters combined and the process repeated until a small sample was obtained.

The samples obtained by quartering were mounted in a permanent mounting medium. The selection of this mounting medium was important since the refractive index of the medium plays a major role in the identification of heavy minerals, and aids in the measurement of roundness and sphericity of quartz grains.

Most light minerals have low indices; most heavy minerals have high indices. Therefore, a synthetic resin with a refractive index of 1.66 was used. This resin divides the range of indices of the heavy minerals, and thus facilitates identification. In mounting the light minerals (quartz, index 1.544, e-1.553) this medium of index 1.66 markedly increases the relief of the grains. The details are accentuated for study and measurement with the camera lucida.

Since the heavy minerals of the first two sieve

sizes (20-48, 48-65) were rock particles instead of minerals, they were discarded. Pettijohn*

*Pettijohn, F.J., Op. cit., p 319.

points out that

"It is known from observation that the heavy minerals of a sand are largely concentrated in its finer grades. This is due to the fact that for certain dominant size of quartz and feldspar there is a smaller size of magnetite and like heavy minerals, which are deposited together because they have what Schone called the same settling rates. Consequently, by screening out the coarse fractions, the heavy minerals will be materially concentrated."

Heavy minerals of the four sizes 65-100, 100-150, 150-200, and 200 plus, were mounted on slides for each of the seven stations along the esker. A portion of the remaining unmounted heavy minerals were mounted by using the conventional Canada balsam (index 1.54) as the mounting medium. The appearance of certain minerals was compared in the two different media.

Only sieve size 20-48 was discarded in mounting the light minerals.

Identification of Heavy Minerals.

The identification of heavy minerals was based upon the use of the polarizing or petrographic microscope. Minerals may be distinguished in a number of ways, but for the non-opaque mineral grains the optical method is the most acceptable. The polarizing microscope is a compound

microscope and differs from the ordinary compound instrument since it is equipped with two prisms which produce plane polarized light. The manner of passage of the polarized light through the minerals serves as the identification of that mineral.

A mechanical stage was used to expedite the mineral count. This stage holds the mount to be studied and is so constructed that the mount can be moved in either of two straight paths at right angles in a horizontal plane. This eliminates the possibility of overlapping microscopic fields.

The mounts of three different sieve sizes (65-100, 100-150, 150-200) for each station were counted and identified. The 200-plus size was ignored since the grains were very small and difficult to identify. This meant counting the heavy minerals on 21 slides with an average of 400 grains per slide. Approximately 8400 heavy mineral grains were counted and identified in this study.

Eighteen different mineral species were encountered; fourteen were constant through all seven stations and all sieve sizes. It is interesting to note that the most frequently occurring mineral is actually a composite aggregate or compound mineral. The grains are greenish white, semi-opaque with a "dirty" appearance. H. B. Milner*

Milner, H.B., Sedimentary Petrography: D. Van Nostrand Co., New York, 1929, p 89.

"the petrography of sedimentary rocks is frequently complicated by an inherent difficulty of identifying certain rock-fragments, composite grains (compound minerals), iron- or carbon stained flakes, green or white semi-opaque grains of "dirty" appearance, and a number of other possibilities well appreciated by those who spend much time in searching mineral concentrates under the microscope."

Careful investigation of the 48-65 sieve size revealed that larger fragments of the same composite grain were composed of quartz, iron ore, and chloritic matter.

Following is the list of the minerals found in the Mason esker and the characteristics by which identification was made:

Hornblende: Complex silicate of Fe, Mg, Ca, Al, and Na.

Crystal system: Monoclinic.

Color : Var Arfvedsonite - blue green.
Var Common Hornblende - green to brown.

Index : a, 1.658-1.698; b, 1.670-1.719; c, 1.679-1.722.

Birefringence : .026-.027.

Optic Figure : Biaxial negative.

Elongation : Positive.

Pleochroism : Marked.

Distinctive Features: Grains elongate; prismatic; inclined extinction; marked pleochroism; common.

Clinopyroxene: (Augite, Diallage, Diopside)
 $\text{CaO} \cdot 2(\text{Mg}, \text{Fe})\text{O}, (\text{Al}, \text{Fe})_2\text{O}_3 \text{ SiO}_2$.
Crystal system: Monoclinic.
Color : Brownish gray to gray-green.
Index : a, 1.696-1.700; b, 1.702-1.718; c, 1.714-1.742.
Birefringence : .018-.043.
Optic Figure : Biaxial positive.
Extinction : 44-48 degrees.

Distinctive Features: Grains usually elongate worn cleavage fragments; poorly rounded; high index; high birefringence; large extinction angle.

Garnet: $R''R'''(SiO_4)_4$ where R'' is Mg, Fe⁺⁺, Ca, Mn.
 R''' is Al, Fe⁺⁺⁺, Cr.

Crystal system: Isometric.
 Color : Pink and colorless.
 Index : 1.70-1.90.
 Distinctive Features: High relief; isotropism; conchoidal fracture.

Chloritic Matter: Essentially silicates of Al, Fe, Mg, and Hydroxyl.

Crystal system: Monoclinic.
 Color : Dirty green.
 Birefringence : .003-.009.
 Distinctive Features: "Ultra-blue" abnormal interference color; compound polarization; pale green color; low birefringence.

Zircon: $ZrSiO_4$.

Crystal system: Tetragonal.
 Color : Colorless.
 Index : $e=1.985-1.991$; $o=1.926-1.936$.
 Birefringence : .0443.
 Optic Figure : Uniaxial positive.
 Elongation : Positive.
 Extinction : Parallel.
 Distinctive Features: Euhedra common; pyramidal terminations; basal grains rare; rod shaped inclusions; high index.

Monazite: $(Ce, La, Nd, Pr)_2O_3 \cdot P_2O_5$.

Crystal system: Monoclinic.
 Color : Yellow.
 Index : $a, 1.786-1.800$; $b, 1.788-1.801$; $c, 1.837-1.849$.
 Birefringence : .049-.051.
 Optic Figure : Biaxial positive.
 Pleochroism : Faint, X-light yellow, Y-dark yellow, Z-greenish yellow.
 Extinction : 2-10 degrees.
 Cleavage : Perfect basal.
 Distinctive Features: Grains rounded, equidimensional often lying on 001; euhedra rare; exhibit same color between crossed nicols as in ordinary light owing to high birefringence; high relief; light yellow color.

Epidote: $\text{Ca}_2(\text{Al,Fe})_3\text{Si}_3\text{O}_{12}(\text{OH})$.

Crystal system: Monoclinic
 Color : Bottle green.
 Index : a, 1.722-1.729; b, 1.742-1.763; c, 1.750-1.780.
 Birefringence : .028-.051.
 Optic Figure : Biaxial negative.
 Pleochroism : Distinct. X-colorless, Y-bottle green, Z-colorless.
 Extinction : 2-5 degrees.
 Cleavage : Perfect basal.
 Distinctive Features: Grains equidimensional, subrounded; distinct pleochroism; bottle green color; high index.

Titanite: $\text{CaO.TiO}_2.\text{SiO}_2$

Crystal system: Monoclinic.
 Color : Pale yellow, light brown.
 Index : a, 1.900; b, 1.007; c, 2.034.
 Birefringence : .134.
 Optic Figure : Biaxial positive.
 Elongation : Negative
 Pleochroism : Weak.
 Extinction : 51 degrees.
 Distinctive Features: Conchoidal fracture; diamond shaped euhedral grains; exhibit same color under crossed nicols as in ordinary light owing to high birefringence; many grains fail to show complete extinction in white light due to high dispersion. The grain turns bluish as the extinction position is reached.

Hypersthene: $(\text{Mg,Fe})\text{SiO}_3$.

Crystal system: Orthorhombic.
 Color : Pale pink and green.
 Index : a, 1.665-1.715; b, 1.669-1.728; c, 1.674-1.731.
 Birefringence : .009-.016.
 Optic Figure : Biaxial negative.
 Elongation : Positive.
 Pleochroism : Marked. X-pink, Y-yellow, Z-green.
 Extinction : Parallel.
 Distinctive Features: Worn elongate cleavage fragments. Highly colored, thin, brown, plate-like inclusions (schiller structure); low birefringence; parallel extinction; striking pleochroism.

Orthopyroxene: (Enstatite, Bronzite) $(\text{Mg,Fe})\text{SiO}_3$.

Description same as hypersthene except enstatite is nearly colorless and is bi-axial positive. Enstatite, bronzite, and hypersthene are members of an isomorphous series in the orthorhombic pyroxene group.

All Others:

Rarely grains of biotite, tremolite, zoisite, leucoxene, tourmaline, rutile, and staurolite are encountered. Since collectively they make up less than 1% of each heavy mineral suite, their description is omitted.

The results of this heavy mineral frequency count are presented in tabular form on pages 25, 26, and 27. It is immediately apparent that the mineral suites and frequencies are similar for all seven stations. This establishes a definite homogeneity for the seven mineral suites.

Roundness and Sphericity Measurement of Quartz Grains.

The quartz grains were studied in an effort to determine if a relationship could be established between the quartz grains at the seven different stations of the esker. In other words, how does the roundness and sphericity compare at the various stations?

Hakon Wadell*

*Wadell, Hakon, Volume, Shape and Roundness of Quartz Particles: Journal of Geology, vol 43, pp 250-280, 135.

was one of the first to differentiate between sphericity and roundness and to show that these are independent variables. Wadell pointed out that roundness is concerned

with the sharpness of the corners of a grain whereas sphericity is a ratio between the length and breadth of a grain.

Wadell devised a method for measuring roundness and sphericity but it is very time-consuming. Geology students at Michigan State College combined the ideas of Wadell and N. Allen Riley*.

*Riley, N. Allen, Projection Sphericity: Journal of Sedimentary Petrology, vol 11, pp 94-97, 1941.

Riley devised a method by which sphericity can be measured rapidly with accuracy. Mr. George T. Schmitt, graduate student at Michigan State College, devoted a great deal of time and effort to this problem and is responsible for the development of the method used in this paper. Mr. Schmitt drew a concentric circle protractor similar to the one used by Wadell, on white paper rather than celluloid. By means of a camera lucida, the images of the grains were projected to the concentric circle protractor. The diameters of the inscribed and circumscribed circles (sphericity) of each quartz grain, and the arc of the corners of each grain (roundness) could be obtained simultaneously.

The writer used the method described above with

Wadell's formula for roundness: $\frac{(r/R)}{N} = P$

(r/R) is the sum of the roundness values of the corners.

N is the number of corners in the given plane.

P is the total degree of roundness.

and Riley's formula for sphericity: $\phi = \sqrt{\frac{1}{D_c}}$

i is the diameter of the inscribed circle.

D_c is the diameter of the circumscribed circle.

Two sieve sizes (48-65, 65-100) were measured. Some authors believe that finer particles would be subjected to an excessive amount of fracture and therefore would not give satisfactory roundness and sphericity values. At least fifty quartz grains per slide, with an average of ten corners per grain, were measured. Fourteen slides with a total of 7000 measurements was sufficient to give a fair roundness and sphericity value.

The comparison of the values obtained for the two sieve sizes at the seven stations is shown by Figs 5 and 6. It is immediately apparent that there is a close correlation between the roundness and sphericity values for all samples. It is interesting to note that the roundness increases from north to south. It is an accepted fact that the subglacial streams in this area flowed southward. It has also been generally assumed that sand grains become progressively more round as they are transported. Theoretically, the direction from which a sediment came could be determined if a progressive increase in roundness were detectable. The roundness fig-

ures obtained for the Mason esker support the theory that the subglacial stream must have flown southward.

CONCLUSIONS

Earlier in this paper the theories that have been advanced by well-known geologists for the origin of eskers were summarized. It was also pointed out that probably all of these theories were necessary for a complete explanation of the origin of eskers. This paper is concerned with the Mason esker and the application of a detailed petrographic study of the esker sands as an aid in the determination of the origin of that particular esker.

We are now ready to compare the results of this petrographic study with each theory and attempt to determine if the results favor any one theory for the origin of the Mason esker.

Inspection of the graphs (Figs. 7,8,9,10,11, and 12) shows immediately that the heavy mineral suites are identical and that the mineral frequencies are very similar for all seven stations in the esker. This strongly suggests that the Mason esker is a continuous, homogeneous deposit and that deposition was simultaneous along its length. These results lend support to Davis's*

*Davis, W.M., Op cit.

subglacial channel theory whereby the sands carried by the

subglacial stream were deposited in a continuous narrow channel. It would be expected that the composition of the deposit at the beginning of the channel should be very nearly the same as at the end.

These results do not exclude the possibility of englacial or superglacial origin. However, Trowbridge's*

*Trowbridge, A.D., Op. cit.

theory is difficult to explain in the light of the results obtained in this study. Such a theory proposes headward building of the esker by successive kames. This dumping action at the margins of the retreating ice sheet would result in a more heterogeneous mineral suite. If a time factor were involved this would be especially true. It is not known how long it took the glacier to retreat the length of the Mason esker or if it were an uninterrupted retreat. It seems possible that shortly after the ice front had advanced into a new lithologic province, climatic conditions might change causing the glacier to retreat. The detrital material carried within the ice would be deposited. The mineral suite and frequency found in the first kame deposited during the retreat would be governed to some extent by the lithologic province in which the kame was deposited. This would obviously cause a variation in mineral suites in a series of successive kames as Trowbridge postulates.

Perhaps an even stronger argument against the "drawn out kame" theory is presented if we assume that the foremost part of an advancing glacier will pick up the bulk of its detrital material from the earth's surface. As the ice advances, scouring and gouging deeper into the earth's crust, new material is incorporated into the ice. Widely varying strata might be encountered as the ice cut downward. If the strata were the same for great depths, mineral suites would still differ since the uppermost rocks may consist of alteration products. For example, hornblende may alter to chlorite, biotite, magnetite; olivine may alter to antigorite, magnetite or some pyroxene; pyroxene may alter to the secondary hornblende, urallite.

If the ice were eroding an igneous structure, different minerals might be encountered as the ice approached the center of the structure. This may be explained by the order of crystallization around the periphery of an igneous mass, the more basic minerals crystallizing near the edge. With a retreat of the glacier, the ice front would have a heavy concentration of the minerals first encountered by the gouging, scouring, advancing ice. The first kame deposited would contain these minerals and with headward building of successive kames, the mineral suites and frequencies should vary.

However, under the same conditions (new lithologic provinces, varying strata, or igneous structures), the

deposits of a subglacial stream would still be homogeneous since this is an aggrading stream. Such a stream does not scour and erode the surface over which it flows. The sediment which is deposited throughout the length of the stream channel has been well sorted. Any new source material would be distributed by the stream along the length of the channel since it is a simultaneous deposition. It is possible that the mineral suites might vary in a subglacial stream but the most important fact in this study is that the mineral suites do not vary. Therefore, it is difficult to accept any explanation for the origin of the Mason esker other than Davis's subglacial stream channel theory.

The results of the sphericity and roundness measurements of quartz grains give further support to Davis's subglacial theory. Figs. 5 and 6 show that the roundness and sphericity values are similar at all stations. Roundness increases slightly to the south, the direction of flow of the subglacial stream. This slight change in roundness suggests progressive abrasion of the grains as they are rolled southward.

The sphericity is also nearly identical for all stations, but decreases southward. Stream abrasion may increase roundness but decrease the sphericity of grains. Quartz has no cleavage. The rolling and abrasion causes

quartz grains to become more elliptical thus decreasing the sphericity.

The retreating kame hypothesis again comes under criticism since the roundness and sphericity of the individual particles in each kame probably would not be identical.

In conclusion, this petrographic study clearly indicates that the Mason esker is a subglacial stream channel deposit. The results prove conclusively the advantage of a statistical approach as an aid in determining the origin of glacial land forms.

FREQUENCY PERCENTAGE OF HEAVY MINERALS

65-100 Sieve Range

Station	1	1A	2	3	4	5	6
Compound Aggregate	36.4	39.6	37.3	38.0	35.8	35.9	37.5
Hornblende (arf.)	18.3	17.2	17.1	20.0	19.3	18.3	20.6
Chloritic Matter	11.5	11.9	12.9	15.9	10.2	10.4	8.5
Garnet (Pink)	9.8	6.3	8.7	6.7	9.4	6.1	6.7
Garnet (Colorless)	7.8	5.0	7.0	2.6	8.0	9.5	8.5
Hornblende (Common)	6.0	4.6	4.3	6.4	6.6	8.4	4.9
Clinopyroxene	5.0	7.8	6.6	7.3	5.2	4.4	6.7
Epidote	3.2	4.6	2.1	0.9	3.7	1.7	1.2
Hypersthene	1.6	1.3	2.8	0.9	0.9	1.0	3.0
Titanite	0.4	Tr	0.4	0.9	0.9	1.0	0.6
All Others	0.0	1.7	0.8	0.4	0.0	0.0	1.8

TABLE 1

FREQUENCY PERCENTAGE OF HEAVY MINERALS

100-150 Sieve Range

Station	1	1A	2	3	4	5	6
Compound Aggregate	30.4	27.2	30.1	24.7	29.8	25.9	26.2
Hornblende (Arf)	15.0	19.0	19.2	15.7	15.0	18.9	17.5
Hornblende (Common)	12.0	9.2	16.0	16.8	16.0	13.9	8.8
Clinopyroxene	10.0	9.7	6.6	8.6	7.0	7.4	8.2
Garnet (Colorless)	8.7	8.1	7.6	7.8	10.0	10.9	8.6
Garnet (Pink)	5.5	4.7	4.7	6.8	6.3	6.9	6.5
Chloritic Matter	8.1	9.7	7.5	5.8	8.2	5.7	7.2
Epidote	3.9	4.5	2.5	4.4	0.7	3.6	3.8
Orthopyroxene	2.6	0.8	Tr	2.4	0.3	Tr	1.7
Hypersthene	1.6	2.0	2.5	1.8	1.9	1.8	1.4
Titanite	0.6	0.7	Tr	1.6	Tr	1.8	1.4
Zircon	Tr	2.2	1.1	1.3	1.5	2.2	1.7
Monazite	1.6	1.2	1.4	1.3	2.6	1.0	2.1
All Others	0.0	1.0	0.8	1.0	0.7	0.0	2.1

TABLE 2

FREQUENCY PERCENTAGE OF HEAVY MINERALS

150-200 Sieve Range

Station	1	1A	2	3	4	5	6
Compound Aggregate	22.8	26.4	27.6	25.3	24.9	27.0	24.3
Hornblende (Arf)	20.3	20.0	22.8	20.8	19.8	21.9	19.3
Hornblende (Common)	11.2	10.5	10.7	9.5	10.6	10.3	9.7
Clinopyroxene	7.0	7.3	7.7	7.6	7.7	7.9	8.1
Garnet (Colorless)	11.7	10.7	11.2	11.8	10.8	8.5	10.7
Garnet (Pink)	1.6	4.6	1.9	4.7	5.2	2.0	5.7
Chloritic Matter	5.9	3.1	5.8	5.4	5.0	7.2	4.0
Zircon	3.9	4.0	1.9	3.3	4.3	4.6	5.4
Monazite	3.1	1.8	1.1	2.4	1.1	3.9	3.0
Epidote	5.5	3.7	2.7	3.0	5.2	3.3	2.7
Titanite	3.1	1.2	1.4	1.1	2.0	3.3	2.0
Hypersthene	2.3	4.0	2.7	2.2	1.8	Tr	3.4
Orthopyroxene	1.6	1.2	Tr	1.6	Tr	Tr	1.0
All Others	0.0	1.5	2.5	1.3	1.6	0.0	0.7

TABLE 3

FIG. 1

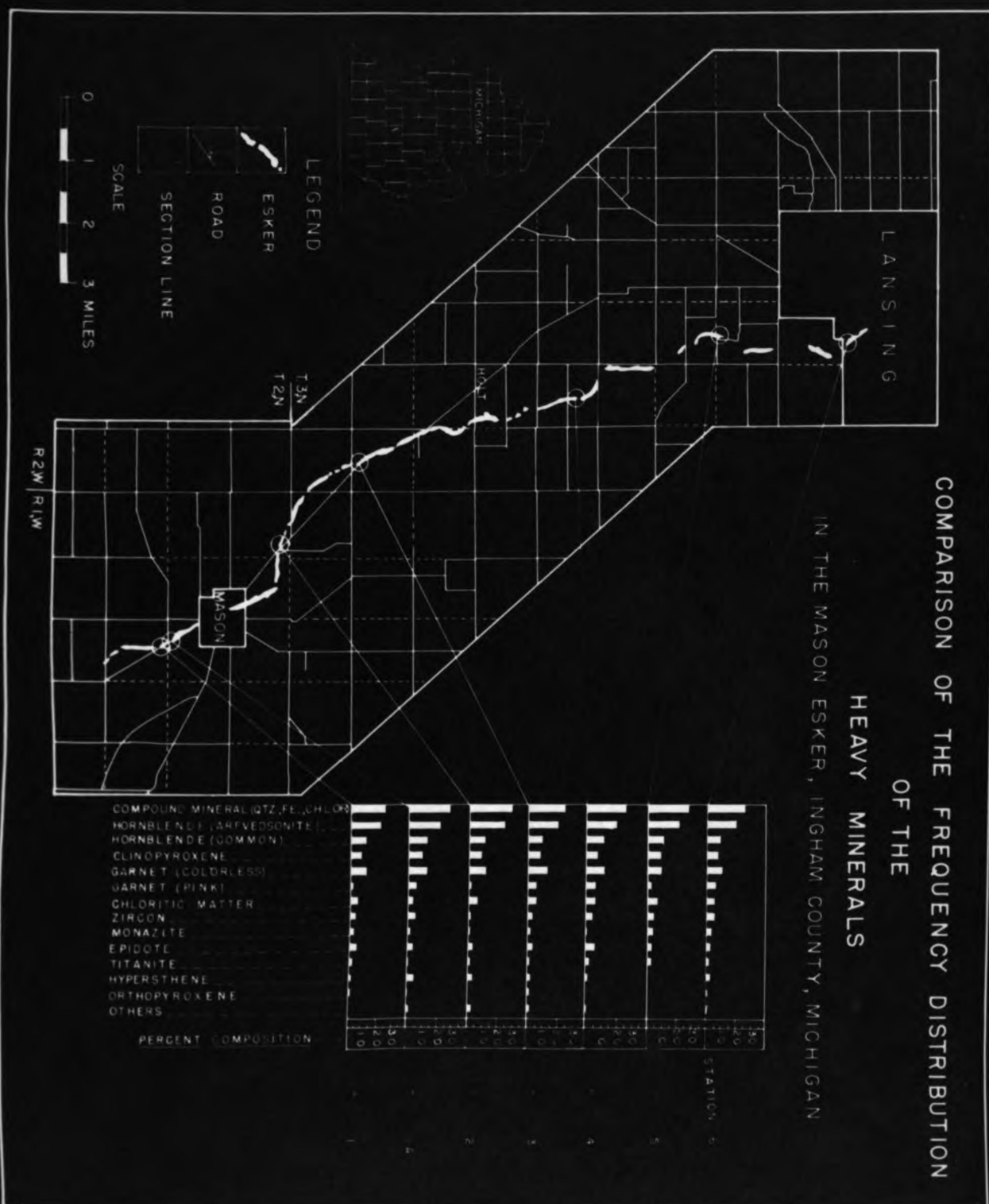


FIG 2

PERCENTAGE OF CARBONATE
IN MASON ESKER SAND

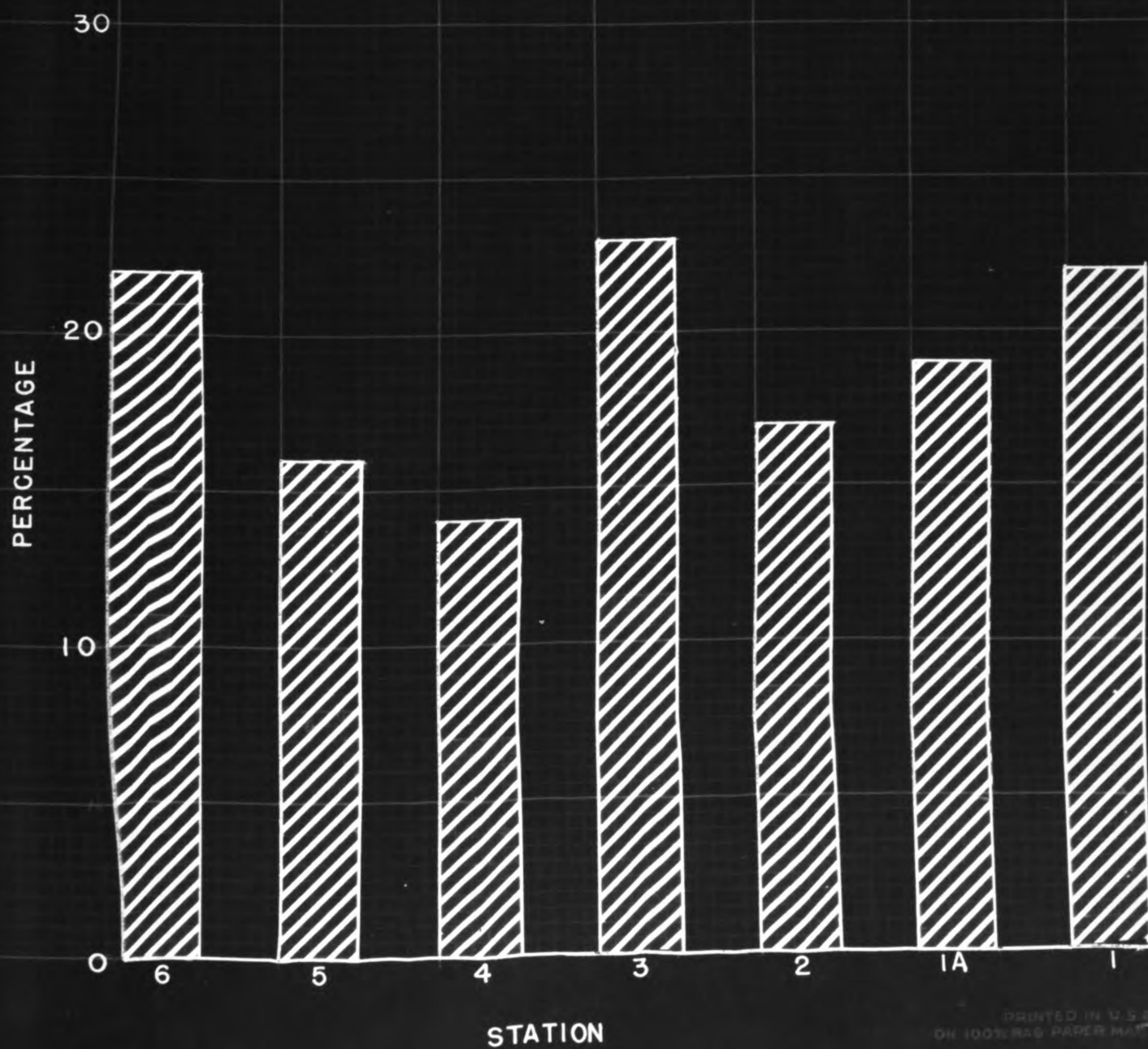


FIG 3

WEIGHT PERCENT ANALYSIS OF SAND

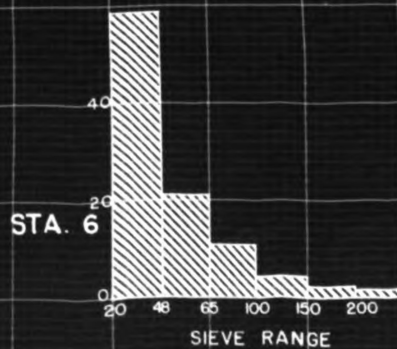
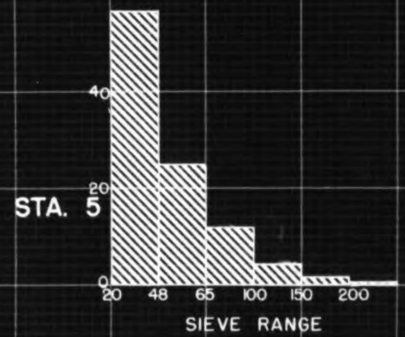
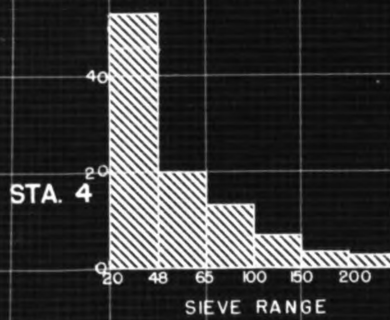
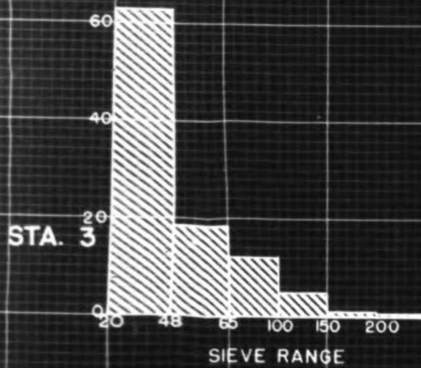
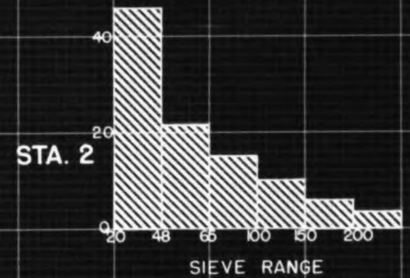
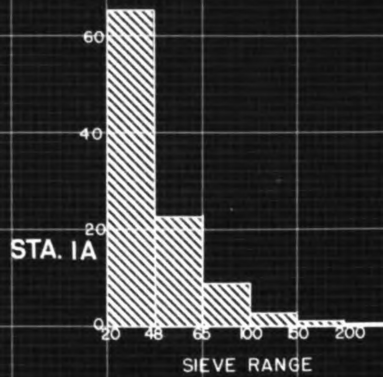
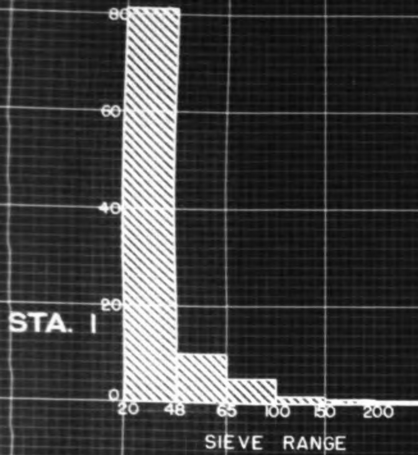


FIG 4

PERCENTAGE OF HEAVY MINERALS
IN MASON ESKER SAND

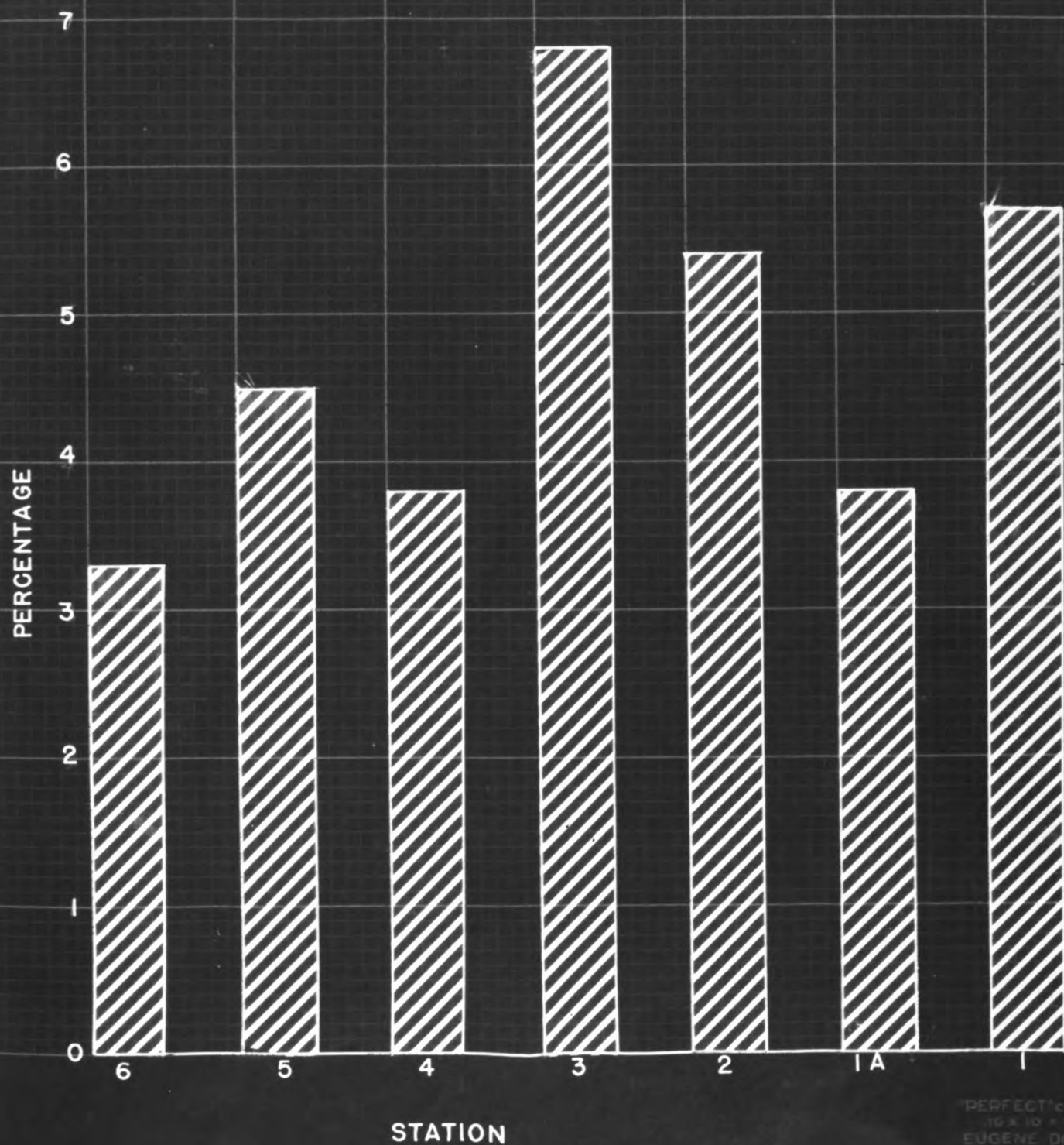
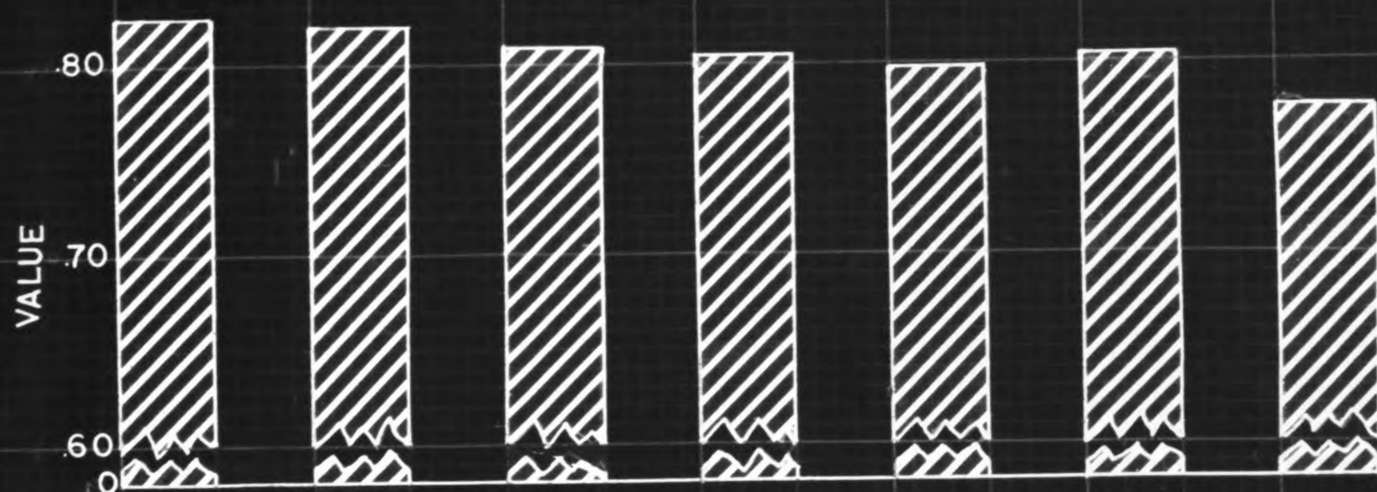


FIG. 5

COMPARISON OF SPHERICITY VALUES OF QUARTZ

GRAINS IN 48-65 SIEVE RANGE IN THE MASON ESKER



COMPARISON OF ROUNDNESS VALUES OF QUARTZ

GRAINS IN 48-65 SEIVE RANGE IN THE MASON ESKER

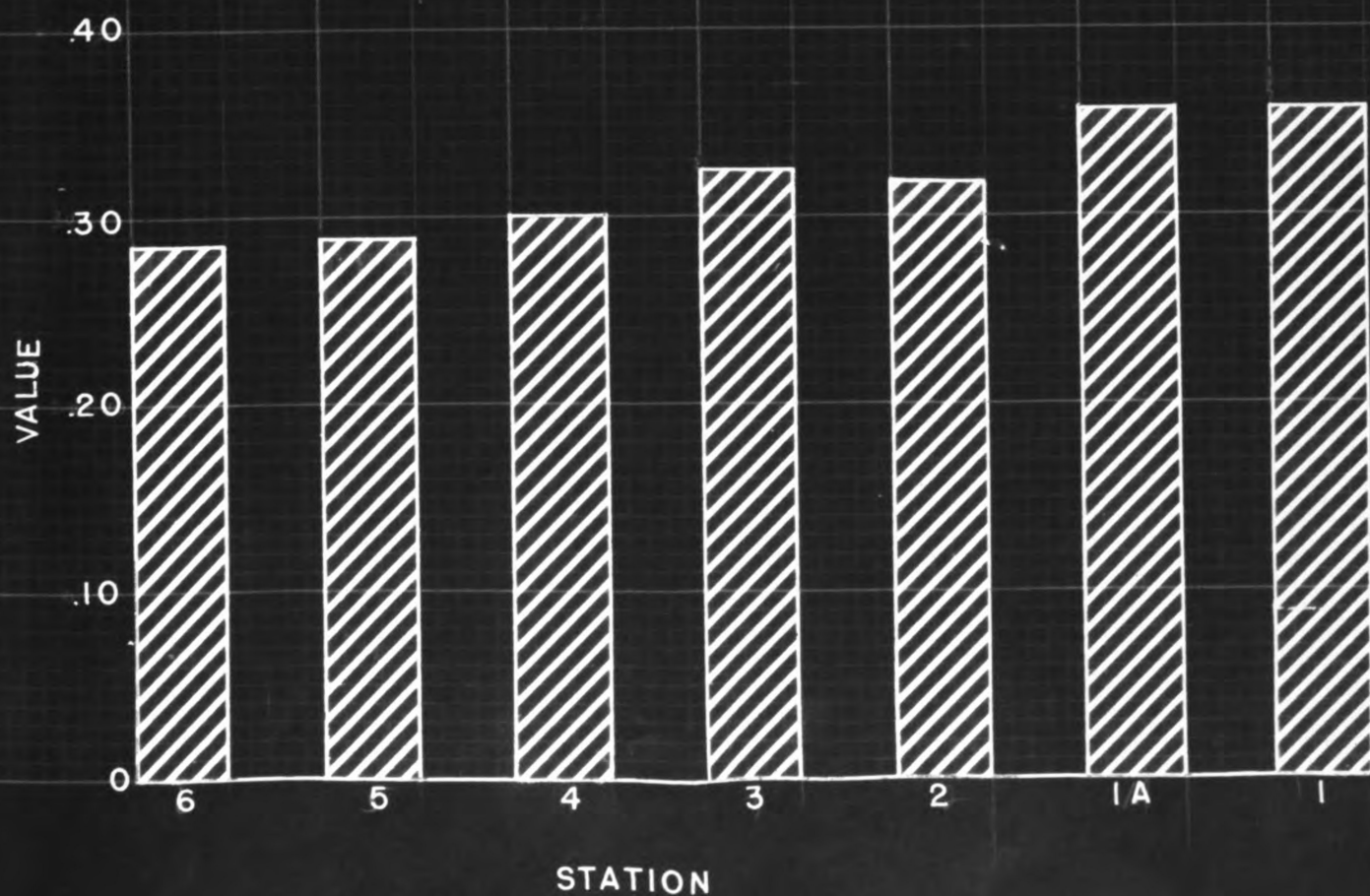
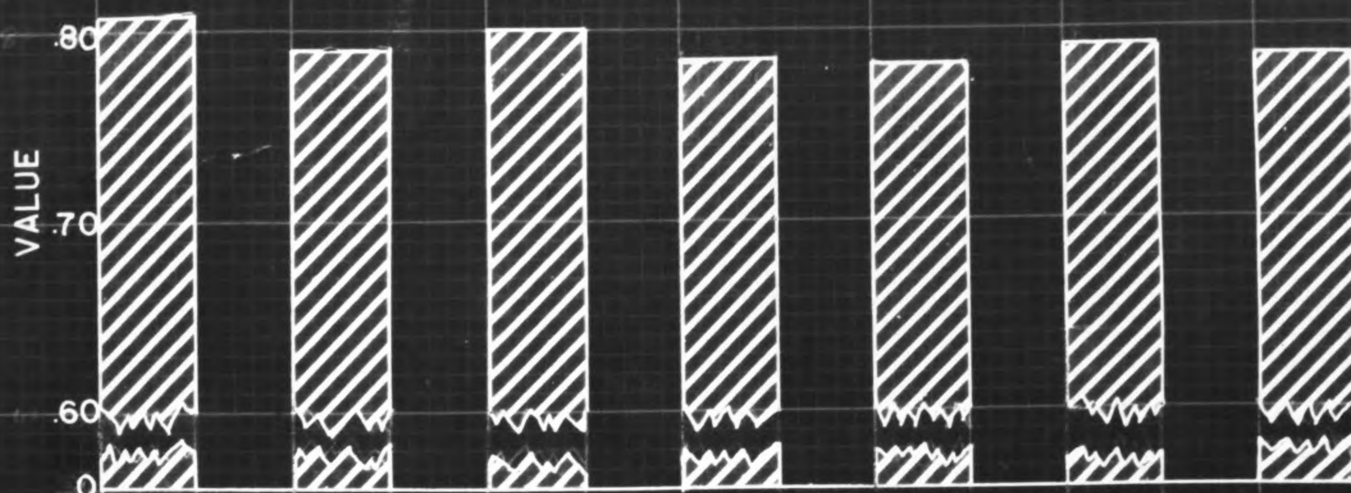


FIG. 6

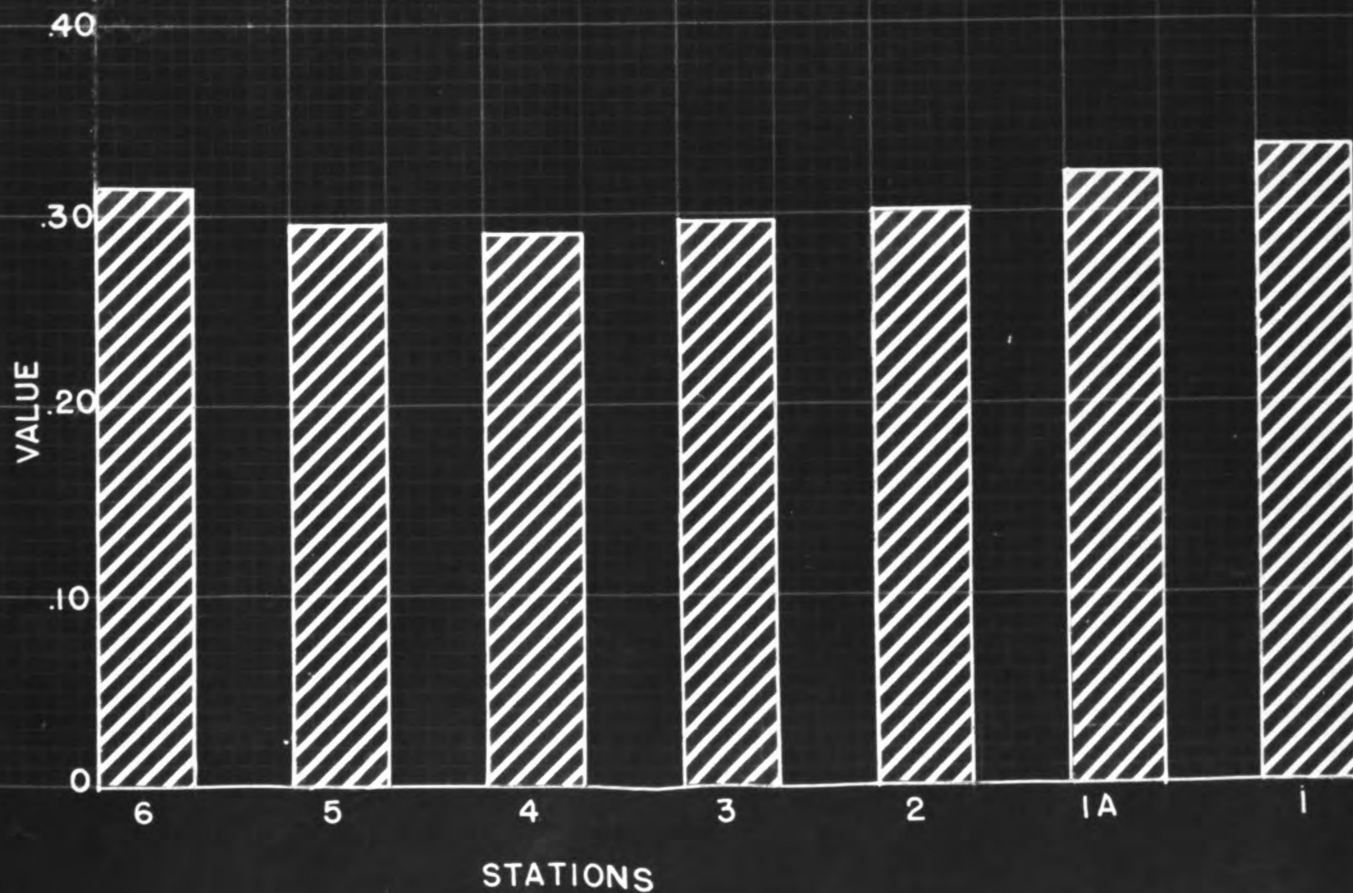
COMPARISON OF SPHERICITY VALUES OF QUARTZ

GRAINS IN 65-100 SIEVE RANGE IN THE MASON ESKER



COMPARISON OF ROUNDNESS VALUES OF QUARTZ

GRAINS IN 65-100 SIEVE RANGE IN THE MASON ESKER



FREQUENCY PERCENTAGE OF HEAVY MINERALS

65-100 SIEVE RANGE

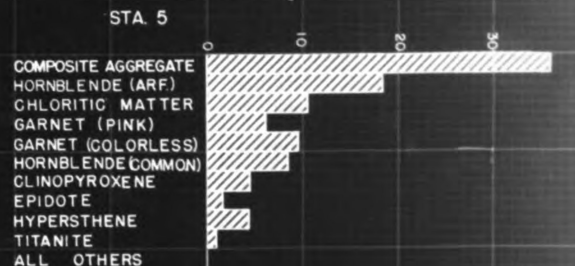
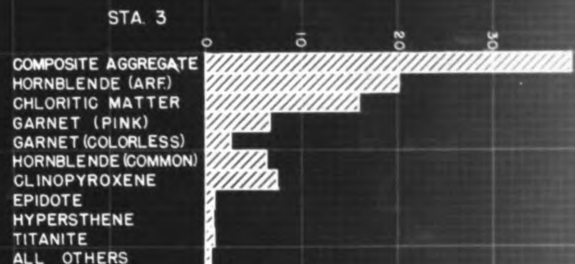
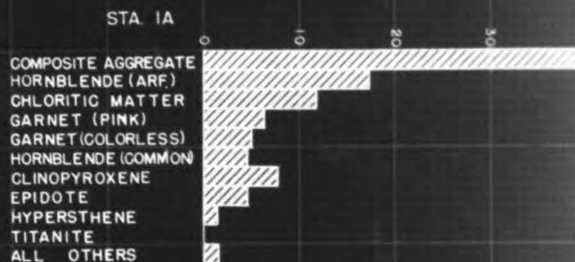


FIG. 8

FREQUENCY PERCENTAGE OF HEAVY MINERALS

100-150 SIEVE RANGE

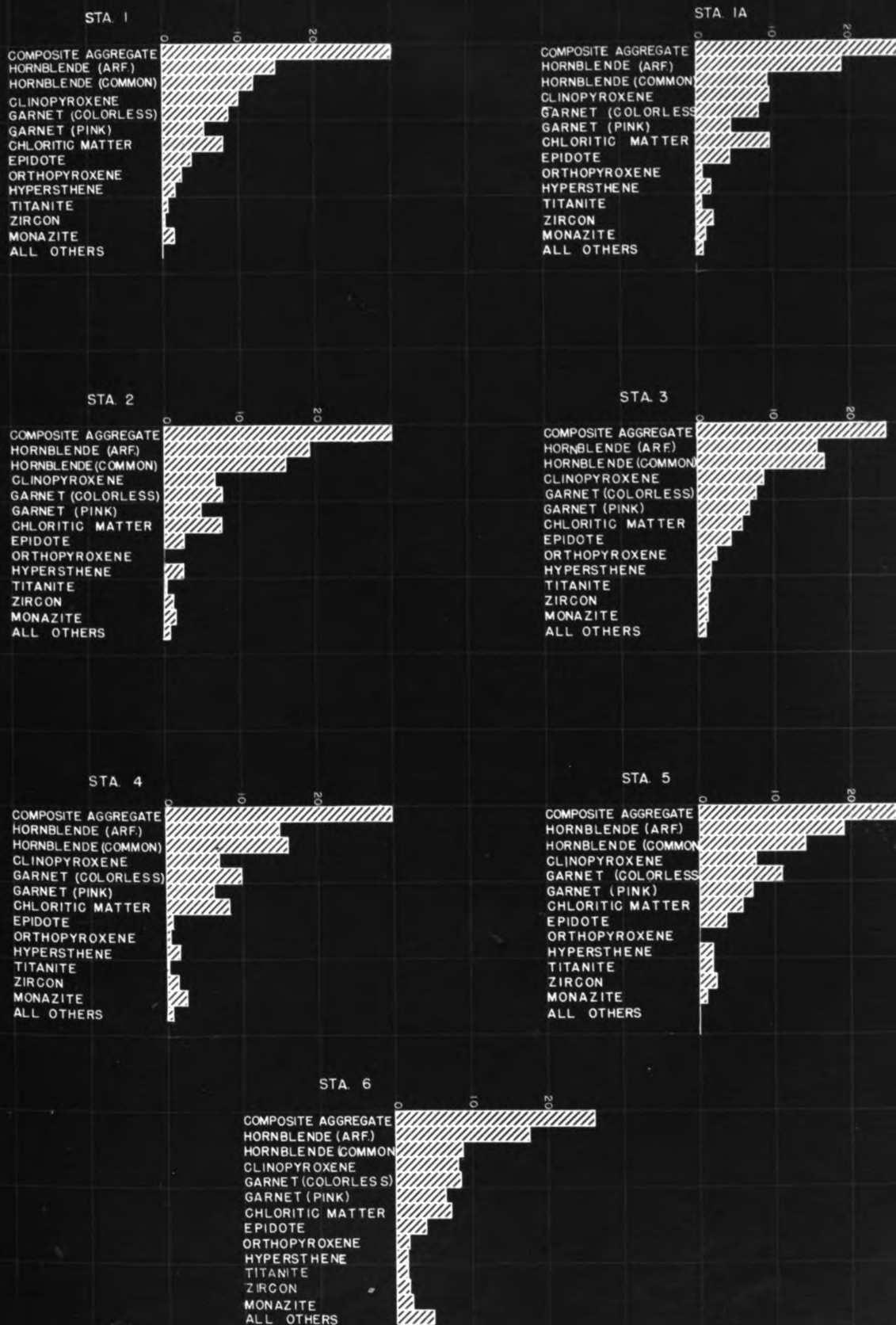


FIG. 9

FREQUENCY PERCENTAGE OF HEAVY MINERALS

150-200 SIEVE RANGE



FIG. 10

GRAPH SHOWING SIMILARITY OF THE SEVEN CUMULATIVE CURVES
REPRESENTING THE HEAVY MINERAL FREQUENCY
WITHIN THE MASON ESKER

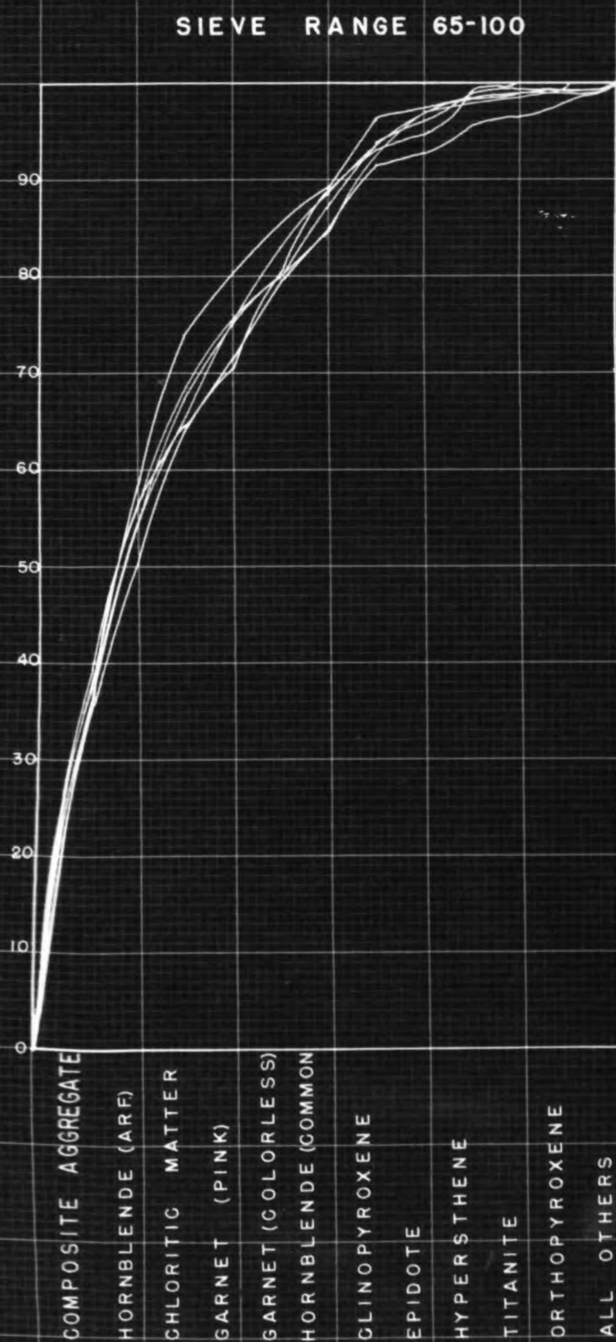


FIG. 11

GRAPH SHOWING SIMILARITY OF THE SEVEN CUMULATIVE CURVES
REPRESENTING THE HEAVY MINERAL FREQUENCY
WITHIN THE MASON ESKER

SIEVE RANGE 100-150

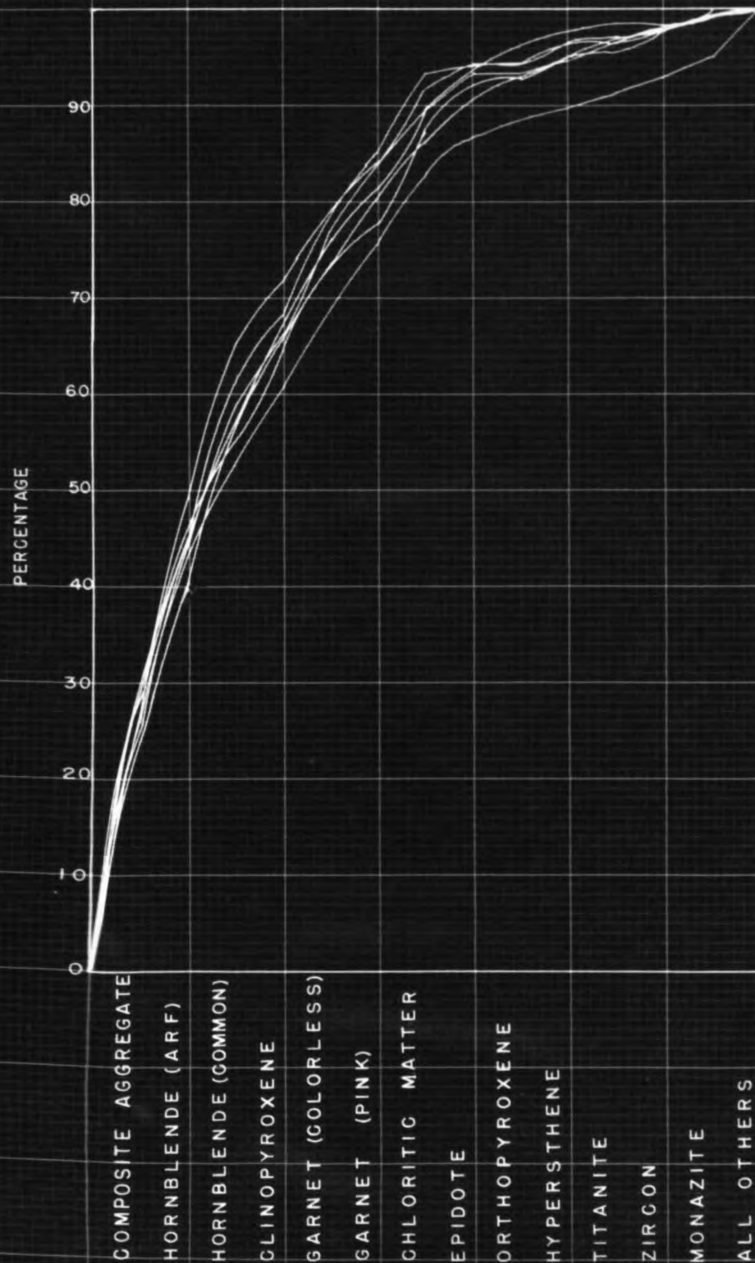
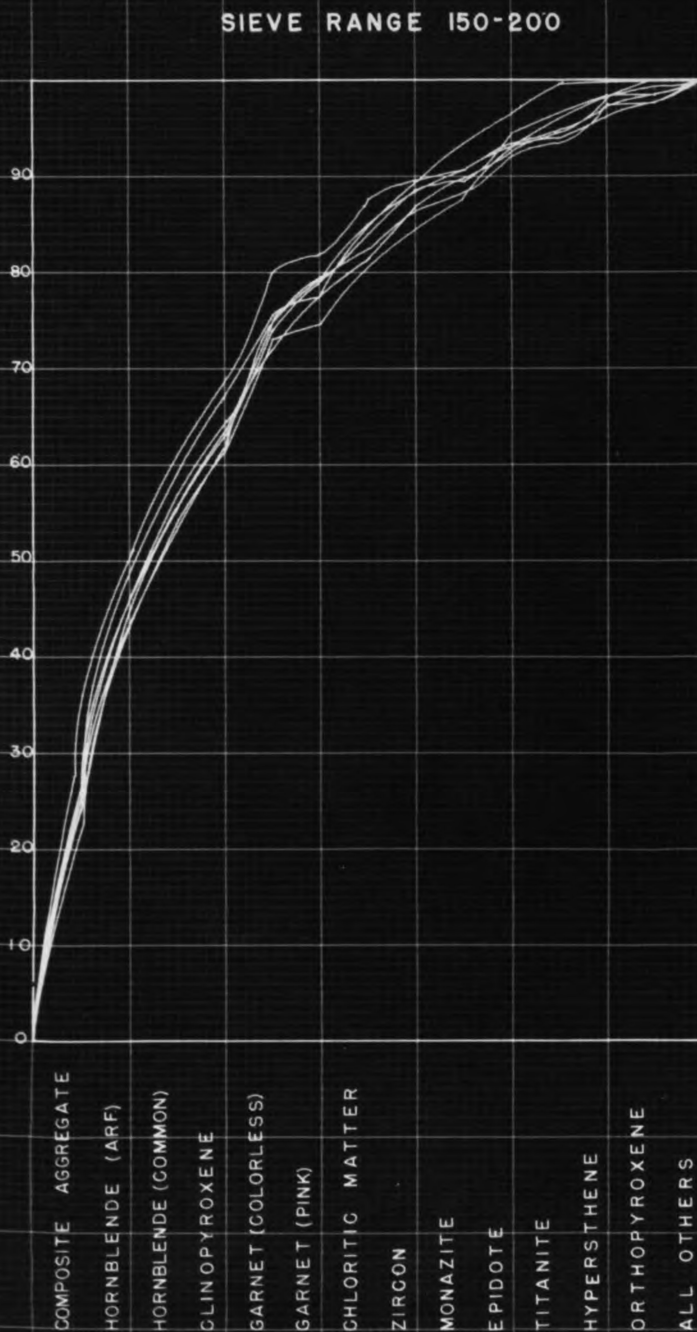


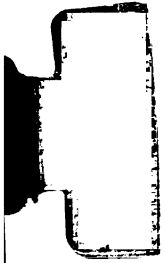
FIG. 12

GRAPH SHOWING SIMILARITY OF THE SEVEN CUMULATIVE CURVES
REPRESENTING THE HEAVY MINERAL FREQUENCY
WITHIN THE MASON ESKER





100-100000



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