

HEAVY MINERAL INVESTIGATIONS OF SOME PODSOL SOIL PROFILES
IN MICHIGAN

By

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INTRODUCTION

In a study of the development of podsoles it is desirable to include an investigation of the heavy minerals. Very little information can be found on the heavy minerals of podsoles in the United States; none can be found on Michigan podsoles. To recognize geological differences in soil horizons, to determine the intensity of the weathering processes in various horizons, and to account for the observational differences in the soil profiles have been major obstacles to the student in the study of soil genesis and development. Recent improvements in the preparation of soils for petrographic analysis and newer techniques in the separation and microscopic identification of soil minerals have aided in more quantitatively determining the changes that may have progressed within soil profiles.

This investigation was an outgrowth of observations on soil profiles made while conducting a land type survey in Charlevoix and Presque Isle Counties of Michigan. Several theories were advanced to explain the profile differences in the various soils. It was believed that through the utilization of the recent techniques in the study of heavy minerals and through an analysis of the data supplied by these techniques certain morphological peculiarities observed in some Michigan podsol profiles might be explained.

REVIEW OF LITERATURE

The study of the heavy minerals in podsoles has not been very extensive. This has been due in part to the lack of suitable techniques for the separation and positive identification of the

heavy minerals. Recently more simplified petrographic methods have enabled the less highly trained petrographer to identify minerals in soils.

Cady (3) differentiated the mineralogical characteristics of podsoles from brown podsollic soils. The heavy minerals in the A horizon of podsoles were decidedly less than those in the C horizon. The minerals hornblende and hypersthene weathered rapidly while magnetite and garnet were little affected. In the A and C horizons of the brown podsollic profiles, the heavy minerals were found in similar amounts.

Richard and Chandler (33) investigated three strongly developed podsol profiles from Quebec Province, Canada and found that hornblende and to some extent hypersthene weathered rapidly in the A₂ horizon whereas it was only slightly weathered in the C horizon.

Jeffries and White (22) showed that in the Leetonia sand (podsol) zircon and anatase were abundant and typical; tourmaline, rutile, muscovite, chlorite, epidote, barite, magnetite, and leucoxene were present but not in sufficient amounts to be typical.

The most recent procedures for the isolation and microscopic identification of the heavy minerals have been outlined by Marshall and Jeffries (28). These include methods for the removal of incrusting substances and oxide coatings, procedures for the separation of the soil minerals, and aids for mounting and counting the separated soil minerals.

Many workers, Cady (3), Haseman and Marshall (16), Humbert

and Marshall (17), Marshall and Jeffries (28), Marshall (27), McCaughey and Fry (29), Mickelson (30), and Richard and Chandler (33) have investigated the use of the resistant heavy minerals such as zircon, tourmaline, garnet, anatase, rutile, and magnetite as indices of soil maturity and development.

Haseman and Marshall (16) have reviewed thoroughly the various minerals resistant to conditions of weathering. Zircon if present in sufficient quantities seems to be the ideal immobile indicator for measuring changes in profile development.

Dryden and Dryden (9) in comparing the resistance to weathering of fresh and weathered Wissahickon schist from Pennsylvania and Maryland found zircon and green hornblende to be more resistant than garnet. Goldich (13) has reported opposite results on an amphibolite from the Black Hills; garnet was more resistant than hornblende. This may be attributed to the differences in climate, slope, or vegetation.

Other workers have stressed the light minerals in explaining soil formation and development. Fieger and Hammond (11) studied the effect of cultivating rice and flooding with fresh well water on the minerals of some coastal prairie soils of Louisiana. They found that limonite, hematite, and magnetite are largely lost from the silt fractions of the A, B, and C horizons of the flooded soil. The feldspars, particularly the potassium feldspar, were more stable than the iron oxide minerals.

Jeffries and White (20, 21, 22, 23) investigated podsoles, gray

brown forest soils, and brown forest soils and found that the influence of parent material is of outstanding importance in the development of soils. The minerals of limestone soils from Indiana, Virginia and Pennsylvania were characterized by high amounts of feldspars in the very fine sand fraction. In the Hagerstown series microcline appeared to be the resistant mineral.

Marshall and Jeffries (28) believe that in addition to the heavy minerals certain feldspathic minerals and muscovite may be useful in weathering studies. Microcline, a resistant mineral in some soils, may be utilized to measure changes in profile development.

Jeffries (19) has discussed the recent advances in soil mineralogy. Among these is the use of the double-variation method as a means of determining the exact chemical composition of the soil minerals. If this technique becomes simplified, it may be possible to measure changes in the chemical composition of soil minerals due to weathering.

The methods of determining the quantities of minerals present in a particular fraction have been investigated by many pedologists (3, 12, 16, 18, 28) and petrographers (2, 4, 5, 25, 31). The method generally used is to separate the sand into grade sizes and count the number of particles of each mineral. Then with the following formula (12), the volume is calculated:

$$\text{Percent by volume} = \frac{\text{Number of particles of one constituent} \times 100}{\text{Total number of particles counted}}$$

Chayes (8) determined the average grain weights of sized particles by counting the number of grains per milligram.

The errors involved in heavy mineral studies have been evaluated by Krumbein and Rasmussen (26). They found that after subjecting 24 closely spaced samples of beach sand to heavy mineral analyses the sampling error was about 10 percent, and the errors due to splitting, separating, and counting were of approximately the same order of magnitude.

Rittenhouse (34) from a study of more than 20 species of heavy minerals has calculated the probable errors due to counting. These probable errors are expressed as percent of the heavy mineral's frequency and as percent of the total number of all heavy mineral grains. For example, a counting of 400 grains with a 3 percent frequency would have a probable error of 19.2 percent of 3 percent.

Chayes (7) found that the use of the number of grains counted as an index of the counting error required experimental evaluation. In Chayes' studies the critical range for number frequency analysis was between 500 and 2000 particles. Often the increased accuracy of counting 1000 grains instead of 500 grains is significant. On the other hand, Pye (32) counted 25, 50, 75, 100, 200, and 300 grains from random fields on slides representative of beach sands, sandstone outcrops, and oilwell cores. From his studies 50 grains appeared to be the optimum number to count.

From this review of literature it would seem that an investigation of the heavy minerals in podsoles would provide valuable and needed information in the recognition of various podsoles and a basis for the measurement of the changes within the profile.

COLLECTION AND SAMPLING

Soil profile samples were collected under as near virgin forest conditions as possible. A large L-shaped pit was dug for each of the profiles. Horizontal variations were taken by sampling along both arms of the "L"; large samples approximating 50 pounds were taken of each horizon.

DESCRIPTION OF SOIL TYPES

Two groups of podsol soils were investigated, namely: Emmet, Kalkaska, and Wallace sands which were tentatively segregated as Group I; and Grayling, Rubicon, Roselawn, and Eastport sands hereafter designated as Group II. Group I is characterized by a stronger expression of morphological features of typical podsol profiles than is Group II. The Kalkaska and Emmet sands supported a forest cover of hardwoods, whereas the other types supported a pine cover. Veatch (41) estimates the total area in Michigan of the soils in Group I to be 1,350,000 acres; in Group II, 4,200,000 acres. Where an asterisk appears in the following profile descriptions, a detailed investigation was made of the heavy minerals.

GROUP I, Emmet sand

Emmet sand differs from Kalkaska sand in that it occupies the sand hills, whereas Kalkaska sand occurs on the nearly level sand plains and valley floors. The typical profile where sampled (NW $\frac{1}{4}$ sec. 8, T. 35N., R. 4E., Presque Isle County) consisted of:

- (1) a thin $\frac{1}{2}$ - to 1-inch litter layer, composed chiefly of

partly disintegrated leaves, grasses and wood.

- *(2) a 2- to 3-inch dark-brown to nearly black, slightly acid medium sand layer containing many partly decayed roots and leaves.
- (3) a 6- to 8-inch light-gray, slightly acid, leached, loose medium sand layer.
- *(4) a 6- to 8-inch umber-brown or dark-brown, slightly acid, weakly cemented medium sand layer.
- (5) a 16- to 20-inch grayish-yellow or yellow, neutral medium sand layer.
- *(6) a grayish-yellow, strongly alkaline medium sand extending to a depth of 60 inches.

Kalkaska sand

This type occurs on level, dry, hardwood plains and valley floors. This series was distinguished from the Rubicon, Grayling, and Eastport by its umber-brown sand layer which underlies the ash-gray surface soil and by the greater amount of cementation in the accumulation horizon. The profile, sampled in NE $\frac{1}{4}$ sec. 8, T.32N., R.5W., Charlevoix County, consisted of:

- *(1) a 2- to 3-inch surface layer of dark-brown to nearly black, slightly acid, medium sand mixed with partly disintegrated leaves, twigs, and pieces of wood.
- (2) a 8- to 10-inch light-gray, strongly acid, loose, leached medium sand layer.
- *(3) a 2- to 3-inch umber-brown or dark-brown, strongly acid, weakly cemented medium sand layer.

- (4) a 4- to 6-inch lighter colored dark-brown, slightly acid, weakly cemented medium sand layer.
- *(5) a loose, pale-yellow or gray, slightly acid, medium sand to 60 inches.

Wallace sand

Wallace sand comprises the low pineland ridges which represent old dunes or beach ridges. It differs from the other dry sands sampled in its greater thickness and stronger cementation of the brown horizon. A description of this soil type, collected in NE $\frac{1}{4}$ sec.3, T.33N., R.5E., Presque Isle County, follows:

- (1) a $\frac{1}{4}$ - to $\frac{1}{2}$ -inch dark-brown, slightly acid mat of disintegrated grasses, twigs and pieces of wood.
- *(2) a 2- to 3-inch layer of dark-grayish brown, slightly acid sand mixed with partly decomposed plant roots.
- (3) a 6- to 8-inch loose, ash-gray, medium acid sand layer.
- *(4) a 10- to 14-inch dark-brown, medium acid sand layer, cemented in places into a hardpan. Part of the sample included dark-brown fingers which projected to a depth of approximately 3 feet into the lower horizons.
- (5) a 18- to 20-inch lighter colored dark-brown, weakly cemented, slightly acid sand.
- *(6) a loose, brownish-yellow, slightly acid sand layer sampled to a depth of 70 inches.

GROUP II, Grayling sand

The soils of the Grayling series occur as the very dry, level, sand plains which originally supported a pine vegetation. The

present growth consists chiefly of thickets of jack pine, together with sweetfern and bracken. The profile, sampled in SE $\frac{1}{4}$ sec.7, T.25N.,R.3W., Crawford County, did not have a definite leached horizon but included the following layers:

- (1) a $\frac{3}{4}$ - to $\frac{1}{2}$ -inch dark-brown organic layer, composed chiefly of disintegrated pine needles and grasses.
- *(2) a 3- to 4-inch gray-brown, slightly acid, medium sand layer containing some decaying plant roots.
- *(3) a 20- to 24-inch loose, brownish-yellow, strongly acid, medium sand layer.
- *(4) a pale-yellow, slightly acid, medium sand to a depth of 50 inches.

Rubicon sand

Rubicon sand also occurs on dry, level to undulating plains. Originally the growth consisted chiefly of white and Norway pine. The second growth is mostly jack pine and aspen with large open areas of bracken, sweetfern, and blueberries. This soil supported a little heavier growth of vegetation and has a thicker gray and brown subsurface layer than the Grayling and Eastport sands. The profile, observed in NW $\frac{1}{4}$ sec.33,T.36N.,R.2E., Presque Isle County, consisted of:

- (1) a $\frac{1}{4}$ - to $\frac{1}{2}$ -inch litter layer composed chiefly of disintegrated pine needles and twigs.
- *(2) a 3- to 4-inch dark grayish-brown, very strongly acid, medium sand mixed with charred organic matter and plant roots.

- (3) a 4- to 6-inch ash-gray, leached, very strongly acid, medium sand layer.
- *(4) a 12- to 18-inch brownish-yellow, slightly acid, medium sand very slightly cemented and compacted.
- *(5) a loose, pale-yellow or grayish-yellow, neutral, medium sand extending to a depth of 60 inches.

Roselawn sand

Roselawn sand is found on rolling to hilly terrain. The profile, collected in NW $\frac{1}{4}$ sec.29,T.36N.,R.2E., Presque Isle County, consisted of the following layers:

- (1) a thin $\frac{1}{2}$ - to 1-inch layer of acid litter composed chiefly of twigs and pine needles.
- *(2) a 2- to 3-inch loose mixture of dark-gray, neutral, medium sand, charred organic matter, and plant roots.
- (3) a 2- to 3-inch layer of leached, gray, or light brownish-gray, incoherent, slightly acid, medium sand.
- *(4) a 6- to 8-inch yellowish-brown, slightly acid, medium sand layer very slightly cemented and compacted.
- (5) a 16- to 18-inch layer of yellowish, loose, slightly acid, medium sand.
- *(6) a pale-yellow, loose, very slightly acid, medium sand to a depth of 6 feet. At 6 feet the sand appears slightly coarser.

Eastport sand

Eastport sand occurs largely at the margin of Lake Michigan and Lake Huron on the nearly level to wavy plains and benches.

The profile is weakly developed and does not show as much yellow coloration as the other soils studied. The profile where sampled (SE $\frac{1}{4}$ sec.6,T.35N.,R.5E., Presque Isle County) consisted of:

- (1) a $\frac{1}{4}$ - to $\frac{1}{2}$ -inch dark-gray organic layer comprised chiefly of disintegrated pine needles and grasses.
- *(2) a 2- to 3-inch layer of gray-brown, slightly acid medium sand mixed with many partly decomposed plant roots.
- (3) a 3- to 4-inch layer of gray, slightly acid medium sand.
- *(4) a 13- to 15-inch pale-yellow, loose, slightly acid medium sand.
- *(5) a grayish, loose, slightly acid medium sand layer sampled to a depth of 50 inches.

Hereafter, in the discussion of the soil types, the first layer of each soil profile subjected to a detailed investigation of the heavy minerals will be known as the A horizon; the second, the B horizon; the third, the C horizon.

PRELIMINARY STUDIES

After the field samples were air-dried, they were passed through a 2 mm. sieve. The aggregates remaining on the sieve were gently crushed and again passed through the sieve. The remaining coarse material was discarded. The less than 2 mm. soil material was mixed by rolling on clean paper and quartered to approximately 20 gm. samples.

Determination of Reaction, Free Alumina, Iron Oxide, and Colloidal Silica

The field soil reactions were taken as outlined by Spurway (36).

The pH of the soil was determined in the laboratory with the glass electrode. The ratio of soil to water by weight was 1:1. The mechanical analyses, pH, and organic matter content of the soils are given in Table 2. The pH values of the B horizons are, for the most part, lower than the values for the corresponding C horizons.

The organic matter, free alumina, iron oxide, and colloidal silica were removed as outlined by Truog et al (40). Marshall and Jeffries (28) believe that of the three most commonly used procedures (16, 18, 40), the HCl method (16) more seriously attacks the minerals soluble in acids than Truog's (40) sodium sulphide-oxalic acid method or the Jeffries' (18) aluminum-oxalic acid method. However, since aluminum was to be quantitatively determined in the B horizons, Jeffries' method was abandoned even though it least attacks the minerals.

The methods used for the determination of the free alumina, iron oxide, and colloidal silica were those employed by Robinson (35) and Truog et al (40).

It might be mentioned in passing that the results of this analysis (Table 1) indicate that there was a greater coating of free iron oxide around the particles in the Group I than in the Group II soils. The presence of this greater coating of iron oxide will be explained later in the discussion of "Opaque Minerals".

Mechanical Analyses

The mechanical analyses were determined by the method as outlined by Truog et al (40). The fine sand (0.25-0.02 mm.) was

obtained by sieving the total sands (2-0.02 mm.). Sieving was accomplished by shaking the sand on an 8 cm. number 60 standard sieve with a vertical shake-type apparatus manufactured by the American Instrument Company, Washington, D.C. The average shaking time was twenty minutes. Twenty minutes is usually considered too long to shake sand particles, but recent work of Swineford and Swineford (37) showed that the use of certain mechanical shakers for a period of two hours did not produce a considerable degree of wear or breakage of sand grains.

The mechanical analyses, pH, and organic matter content of the soils are given in Table 2.

With the exception of the organic matter in the A and B horizons these soils consist largely of sand. The percentage of silt, clay, and organic matter is greater in Group I than in the Group II soils.

The results of the mechanical analyses indicate a uniform parent material. A separation of the sand into small size fractions would assist in more definitely determining the uniformity of the parent material.

HEAVY MINERAL STUDIES

Separation of the Heavy Minerals

Heavy mineral separations were made on the fine sands (0.25-0.02 mm.). The heavy liquid used for the separation was a mixture of s. tetrabromoethane and nitrobenzene having a specific gravity of 2.94. Specific gravities were controlled with

a pycnometer.

One to 2-gram samples of fine sand (0.25-0.02 mm.) were placed in small centrifuge tubes which contained the mixture of s. tetrabromoethane and nitrobenzene. These were centrifuged at approximately 750 r.p.m. At 15 minute intervals the tubes were removed, stirred vigorously, and replaced in the centrifuge. After approximately an hour of centrifuging, all the heavy minerals had settled in the tubes. The light minerals were then decanted. The particles clinging to the centrifuge tubes were washed with the mixture of s. tetrabromoethane and nitrobenzene and recentrifuged. The remaining light minerals were decanted and the heavy minerals washed into a beaker with acetone. After being washed twice with additional acetone, the heavy minerals were dried at 70 degrees Centigrade and weighed. Duplicate samples were analyzed.

Mounting of the Heavy Minerals

After the total heavy minerals were weighed, they were spread on a gelatinized slide. This slide was prepared similar to the method described by Fairbairn (10) and Marshall and Jeffries (28). The use of the gelatin coated slides permitted the changing of immersion liquids without losing the grain. No difficulty was experienced in obtaining the Becke tests for refractive indices.

Distribution of the Total Heavy Minerals

The percentage of total heavy minerals in oven dry, organic free soil is given in Figure 1. The results show that there is

a significant increase of heavy minerals in all horizons of Group I (Kalkaska, Emmet, and Wallace) sands over those in Group II (Grayling, Rubicon, Roselawn, and Eastport) sands.

In all the soils, the total amount of heavy minerals was greatest in the C horizon. In the majority of the soils the B horizon had the least amount of heavy minerals. In the C horizon the amount of heavy minerals in Group I is approximately twice that of Group II.

The most striking point brought out by the studies is the great difference in the quantity of total heavy minerals between these two groups of soils.

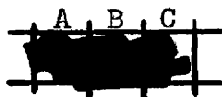
Photomicrographs of the heavy minerals of the C horizons are shown in Plate 4. These heavy minerals were only slightly altered. In Plate 5 the characteristic well-rounded grains of the Wallace sand are readily discernible. No other soil studied had the mineral grains as well-rounded as those in the Wallace sand. Since the sand particles in the C horizon as well as the A horizon were similarly rounded, it is believed that the particles were rounded by water prior to deposition.

Microscopic Identification and Counting of Mineral Grains

After the heavy minerals were mounted on gelatinized glass slides, they were identified, sized, and counted. Before the identification of the soil minerals was undertaken many known detrital mineral mounts were closely studied. Frequent reference was made to the standard texts of Johannsen (24), Milner (31), and Krumbein and Pettijohn (25). Identification of the opaque

minerals was facilitated by a magnetic separation. The heavy minerals were spread out on a flat surface and a horseshoe magnet was passed above the minerals. A piece of thin paper placed over the poles assisted in releasing the magnetized minerals. A preliminary check showed that the horseshoe magnet used would remove magnetite but not ilmenite. Identification of all the heavy minerals was primarily limited to determining the approximate refractive index, pleochroism, birefringence, extinction angle, color, and shape.

A grid micrometer ocular was used to measure the size of the grain. The maximum cross-sectional area of each grain was determined as follows:



The hornblende particle is illustrated in black. The three grid squares are shown below the letters A, B, and C. To obtain the maximum cross-sectional area of the hornblende particle the grid squares that equal the hornblende particle size are counted. In the above figure the maximum cross-sectional area is "3".

Description of Heavy Minerals

Hornblende

Hornblende as it occurred in the materials studied is characterized by elongated prismatic grains, distinct prismatic cleavage, ragged ends, green colors, and weak pleochroism. It occurs as green grains in many shades, dark and gray-green being prevalent

although a few light green and some brown varieties were also found. The color density of the grains usually increased from the margin to the center. Well developed striae were present in some of the grains of the parent material.

Epidote

Epidote was distinguished by its high refractive index and strong birefringence. It occurred as light green or bottle-green, angular to partly rounded grains. Usually it was strongly pleochroic. No inclusions were observed.

Garnet

Garnet was distinguished by its isotropism, high relief, and high refractive index. It occurred primarily as pink, brown, and colorless grains. A few inclusions of quartz were observed. The grains were mostly rounded although some angular irregular grains were present. Many were etched and pitted. Garnet was distinguished from spinel by its index, conchoidal to irregular fracture, and absence of cleavage. Most of the garnet examined was isotropic although a few grains showed anomalous strain features and weak anisotropism.

Opaque Minerals

Magnetite represented approximately 90 percent of the total of all the opaque minerals examined. Of the remainder ilmenite was dominant.

Magnetite occurred as irregular to rounded grains which were a bright black in reflected light and opaque in transmitted light. A few grains exhibited small shiny facets. This mineral was

difficult to distinguish from ilmenite. The higher magnetism of the magnetite was sometimes of assistance.

Ilmenite occurred as iron-black to steel-gray irregular sub-angular grains in reflected light. The grains were opaque in transmitted light. It was generally distinguished from magnetite by its rhombohedral form, conchoidal fracture, more metallic luster, and weaker magnetic properties.

Hematite represented less than 1 percent of the opaque group of heavy minerals. It occurred as reddish-brown irregular earthy grains. The hematite observed in these studies might have been thin films enveloping the magnetite grains.

Leucoxene occurred as white to yellowish-white earthy translucent to opaque rounded aggregates.

Limonite occurred as rounded powdery granules. It was brown in reflected light and opaque in transmitted light. Only traces of limonite were found.

Minor Minerals

The following descriptions are of heavy minerals occurring in small amounts, comprising usually less than 1 percent of the total grains counted.

Zircon was characterized by a very high refractive index, high relief, high order interference colors, and parallel extinction. It represented only a very small percentage of the minerals found. Zircon occurred as colorless elongated prisms, sometimes terminated by pyramidal faces. It nearly always appeared rounded at the crystal edges, particularly the fragmentary grains. In a few grains

inclusions of a colorless mineral with a lesser index than zircon were observed.

Tremolite occurred as colorless and white grains. The habit, cleavage, structure, and fracture appeared similar to that of hornblende although its refractive index was lower and the birefringence stronger. Tremolite was distinguished from diopside by a lower refractive index.

Muscovite constituted less than 1 percent of the minor minerals. It occurred as thin transparent flakes, marked by a low bluish-gray interference color yielding a well-centered biaxial figure.

Tourmaline was present in very small amounts. The grains were relatively small colorless prisms sometimes terminated by pyramids. Tourmaline was distinguished from other minerals by its very strong pleochroism, its rather high birefringence, and its maximum absorption direction.

Presentation of Mineral Count Data

Mineral count data are usually converted to weight percentages (3, 12, 16). The conversion is correct if the grains within the fraction have the same average volumes and the same specific gravity. Coated unknown grains as well as different mineral shapes would also reduce the accuracy of the conversion. In these studies the coated unknown grains were few in number. The shapes of some of the same species of minerals varied tremendously in the C and A horizons. This is vividly brought out in the photomicrographs, Plates 3, 4, and 5. The hornblende is

differently shaped in the A than in the C horizon. It would seem therefore, that the conversion of mineral counts of such varying dimensions to average volumes or weight percentages without correction would result in great errors. Mineral counts were not converted to volume or weight percentages because of the belief that the specific gravity varies as a mineral weathers and the observations that the shapes of the minerals and the frequency of the maximum cross-sectional areas varied within and between horizons.

To show that the frequency distribution of the maximum cross-sectional areas is not the same the Extract from Table 6 is given.

Extract from Table 6

Mineral and Horizon	Number of Particles in Various Horizons							
	Maximum cross-sectional area							
	0.25	0.5	1.0	2.0	3.0	4.0	6.0	10.0
<u>Wallace sand</u>								
Dark Green A	--	96	524	72	34	28	4	2
Hornblende B	--	474	496	88	38	32	8	4
C	--	--	1216	608	246	19	10	13

These results show that in the A horizon the central tendency is near the 1.0 maximum cross-sectional area; in the B horizon between the 0.5 and 1.0; while in the C horizon it is between 1.0 and 2.0.

In the tables and figures to follow, the maximum cross-sectional areas are designated with the class marks; 0.25, 0.5, 1.0, 2.0, 3.0, 4.0, 6.0, and 10.0; and the class numbers 1, 2, 3, 4, 5, 6, 7, and 8. These class marks and class numbers correspond

to the following maximum cross-sectional areas:

<u>Class No.</u>	<u>Class Mark</u>	<u>Maximum cross-sectional area</u>
1	0.25	$(.075)^2 / 4 \text{ mm.}$
2	0.5	$(.075)^2 / 2$
3	1.0	$(.075)^2$
4	2.0	$2(.075)^2$
5	3.0	$3(.075)^2$
6	4.0	$4(.075)^2$
7	6.0	$6(.075)^2$
8	10.0	$10(.075)^2$

Discussion of Results

Garnet

Many workers have studied the use of resistant heavy minerals as indices of soil development. In general, when soils weather the resistant minerals show a relative concentration, whereas the less resistant decrease in relative abundance or disappear completely. Zircon, tourmaline, anatase, rutile, magnetite, and garnet are the most common resistant minerals.

The relative concentration of a resistant mineral can be determined accurately by comparing the size distribution of the entire sample. This is far too time consuming. A comparison of a very narrow grain size may also lead to erroneous conclusions since the choice of a particular grain size is purely arbitrary. The latter is brought out more clearly in the Extract from Table 3 and Table 4.

Extract from Table 3 and Table 4

Mineral and Horizon		Number of Particles in Various Horizons							
		Maximum cross-sectional area							
		0.25	0.5	1.0	2.0	3.0	4.0	6.0	10.0
<u>Rubicon sand</u>									
Brown Garnet	A	--	51	26	27	6	16	8	--
	B	--	10	2	2	2	6	2	6
	C	--	--	3	14	2	26	21	--
<u>Kalkaska sand</u>									
Brown Garnet	A	--	39	61	74	80	30	13	--
	B	--	2	12	26	14	20	24	2
	C	--	--	24	62	38	70	19	--

These mineral counts are of varying magnitude in all the grain sizes and the choice of any one grain size would not give the complete picture of the apparent garnet accumulation. In this investigation the grain size limits were very wide, 0.25-0.02 mm. It was believed that a comparison of the grain sizes within this wide range of grain sizes came nearer to deciding the actual amount of resistant minerals in podzols than a comparison of a very narrow grain size range.

In the Roselawn sand, Table 4, the apparent accumulation of the same size grains in the A horizon occurred in the 1.0, 2.0, 4.0, and 6.0 maximum cross-sectional area groups whereas in the Emmet sand, Table 3, it occurred in the 0.5, 1.0, 2.0, 3.0, 4.0, and 6.0 groups.

The garnet grains were more numerous in all horizons of the Group I than in the Group II soils.

The reduction in the size of the garnet particles in the A

when compared with the C was greater in the Group II soils. This does not necessarily point to a greater degree of weathering in these soils. It must be remembered that the Group I soils originally had a greater number of garnet grains to reduce; therefore they suffered a greater total breakdown.

There was a greater decrease in size of the garnet grains from the C to the B, than from the C to the A horizons in all the soils. This might indicate a greater severity of weathering in the B than in the A horizon.

Opaque Minerals

The opaque minerals were a dominant group of the heavy minerals in all the soils studied. They rank next to the dark green hornblende in total quantity. Magnetite constituted 90 percent of the opaque minerals. Chandler (6) points out that the relative resistance of the more important soil minerals to podsol weathering is as follows:

<u>resistant</u>	<u>moderately resistant</u>	<u>easily weathered</u>
zircon	epidote	hypersthene
magnetite	orthoclase	hornblende
quartz	diopside	plagioclase
garnet		olivine

Cady (3) similarly found that magnetite and garnet seem to be little affected by podsolization.

In these studies, Figures 8, 9, 10, and Table 5, magnetite appeared to weather more readily in the Group I than in the Group II soils. A close examination of Figures 8 and 10, and Table 5 shows that in the Group I soils the mineral grains in the A horizon have decreased in size and total amount when

compared to the C. In the Group II soils (except Eastport) the mineral grains in the A horizon have accumulated.

The B horizons of the Group I soils in general had greater amounts of magnetite than the Group II soils.

A comparison of the data for garnet and the opaque minerals, the two most resistant minerals studied, Tables 3, 4, and 5, and Figures 2 to 10, indicates that garnet was more resistant than the opaque minerals.

The presence of the more intense brown B horizon in the Group I soils has always been difficult to explain. Data from Table 1 and 2 suggest that this intense brown was due to a greater amount of iron oxide and organic matter. Mineralogical examinations, Figures 2 to 16, indicated a greater weathering of the opaque and ferro-magnesian minerals in the Group I soils. Birnbaum, Cohen, and Sidhu (1) have shown that the color change, ranging from yellow to dark brown, of synthetic iron oxide was caused mostly by particle growth. It is believed that the intense brown color due to the inorganic colloids may be explained by the greater original content of the opaque and ferro-magnesian minerals and of the greater decomposition of these minerals in the Group I soils.

Dark Green Hornblende

The mineral count of dark green hornblende is given in Figures 11 and 12, and in Tables 6 and 7.

The A and C horizons of the Group I soils in general contained much greater quantities than the Group II soils. The A horizon of the Emmet sand when compared with the A horizon of the Roselawn

sand had from 2.9 to 13.1 times as many grains. This comparison is shown in the Extract from Table 6 and 7.

Extract from Table 6 and 7

Maximum cross-sectional area	Roselawn A	Emmet A	Emmet A / Roselawn A
0.5	20	65	3.2
1.0	119	1166	9.8
2.0	292	935	3.2
3.0	22	63	2.9
4.0	52	179	3.4
6.0	15	197	13.1
10.0	2	21	10.5

A similar comparison of the Rubicon and Kalkaska A horizons showed that the Kalkaska A horizon had almost $1\frac{1}{2}$ times more grains than the Rubicon.

Eastport sand, because it probably contained recent wind blown material, did not follow the pattern of the A horizon, Group II soils. It contained a very high percentage of small grains; many more than could have weathered from the C horizon. Plate 5 illustrates some of the small hornblende grains.

The A horizons of Kalkaska and Emmet soils (soils that support a hardwood cover) showed a greater count and amount of dark green hornblende than the Wallace, Rubicon, Roselawn, and Grayling soils (soils that support a pine cover).

With the grain size distribution of the C horizon as a basis for measuring the grain size change in the B horizon the following were noted:

- (1) The grains in the B horizons of the Group I soils decreased in size to a greater extent than the Group II

soils (except Eastport).

- (2) The grains in the Eastport B horizon decreased the most in size.

In general it might be stated that the Group I soils have weathered more than the Group II soils.

Photomicrographs of hornblende, Plate 3, show a greater severity of weathering in the A horizons of Kalkaska and Emmet sands than in the Rubicon, Roselawn, Grayling, and Eastport sands.

Gray Green Hornblende

The gray green hornblende grains, Figures 13 and 14, and Tables 6 and 7, were almost as numerous as the dark green hornblende. The Group I soils in general had a greater number of grains than the Group II soils. The A horizon of the Eastport sand, as in the dark green hornblende, contained more grains than could be accounted for by the weathering of the C horizon. As mentioned before these additional grains were probably deposited by wind action.

The B horizons showed the unusual trend of accumulation. There were in most of the soils investigated more grains of all sizes in the B horizons than there were in the C horizons. This might indicate that of all the minerals studied, the gray green hornblende is the most resistant to weathering in the B horizon.

The A horizons of the Kalkaska and Emmet soils (soils that support a hardwood cover) showed a greater amount of gray green hornblende than the A horizons of the Wallace, Rubicon, Roselawn, and Grayling soils (soils that support a pine cover). This

follows the same pattern as given for the dark green hornblende.

To represent the relative degree of weathering between the Group I and Group II soils one soil from each group was chosen. With the grain size distribution of the C horizon as a basis for measuring the grain size change in the A horizon the following were noted:

- (1) The A horizon of the Rubicon sand appeared to be more severely weathered than other soils in Group I.
- (2) The Kalkaska A horizon was the most severely weathered of the Group II soils.
- (3) The grains in the A horizon of the Kalkaska sand had decreased to a greater extent than those in the A horizon of the Rubicon sand.

Epidote

Epidote was not present in sufficient quantities in any of the soils except Wallace sand to justify any definite statements on weathering. The microscopic count for any one grain size was usually less than 25 grains, Figures 15 and 16, and Tables 6 and 7.

The A and C horizons of the Wallace sand had a relatively high content of epidote. Of all the other soils investigated Rubicon ranked second in the total count of epidote grains. The Extract from Table 6 and 7 illustrates that in the C horizon of the Wallace sand the epidote grain count was at least three times as great as the grain count in any of the other sands. In the A horizon of the Wallace sand this dominance was considerably less.

Extract from Table 6 and 7

Maximum cross- sectional area	Wallace C	Rubicon C	<u>Wallace C</u> <u>Rubicon</u>	Wallace A	Rubicon A	<u>Wallace A</u> <u>Rubicon A</u>
0.5	---	---	---	4	121	.03
1.0	400	51	7.8	318	151	2.1
2.0	176	37	4.7	30	23	1.3
3.0	35	13	2.7	10	6	1.7
4.0	16	18	0.9	4	7	0.6
6.0	---	---	---	---	---	---
10.0	---	---	---	---	---	---

Minor Minerals

The minor minerals consisted of tremolite, zircon, muscovite, and tourmaline. The heavy mineral count of these minor minerals from 20 grams of organic-free soil was insufficient to provide any statistically significant comparisons between the Group I and Group II soils. The results represented in Tables 8 and 9 did show that zircon was present in high amounts in the Wallace soil. This apparent accumulation of zircon might indicate a greater severity of weathering in the B than in the A or C horizons of the Wallace soil.

NEUBAUER TESTS

Neubauer tests are included to explain a type of weathering in podsols. It is believed that the heavy minerals, since they constitute a much greater variety and amount of mineral species in these soils, could be utilized to measure the relative growth of plants. Recent investigations by Graham (14, 15) suggested that the organic matter closely surrounding the individual

particles in the B horizons might decompose the fine sand particles for the nourishment of plants. Also, it was thought that the presence of no organic matter as found in the C horizons would provide little nutrient delivery to plants.

The Neubauer tests as used in these studies provided an indication of the relative nutrient delivery of the soil. The procedure and equipment for conducting the Neubauer tests was that recommended by Thornton (39). All cultures were run in triplicate. Rosen rye seed from South Manitou, Michigan was provided by the Farm Crops Section of Michigan State College. The seeds were dusted with Ceresan. The temperature of the air in the Minnesota Seed Germinator was maintained at 20 (plus or minus one) degrees Centigrade. Distilled water was added as required. After 17 days the rye seedlings were removed, washed, air-dried for two hours, and weighed.

The results representing the B and C horizons of all the soils are presented in Plates 1 and 2, and Figure 17. These results showed that the growth on the C horizon of all soils was approximately the same as that on the quartz sand check. The tests suggest that there was no nutrient delivery from the soil minerals to the plant.

The growth on the B horizons showed a decided increase over the quartz sand check. The greatest growth response was found on the Kalkaska and Emmet soils, soils that originally supported a hardwood cover. This indicated a greater nutrient delivery from the B than from the C horizons.

Since the sand particles of the B horizons of the Kalkaska and Emmet soils are higher in coatings of organic matter than most of the other soils studied, it was believed that the presence of the organic matter assisted in the decomposition of the heavy minerals.

The following evidence supports the concept that mineral decomposition in Michigan podzols is due primarily to organic matter:

- (1) A greater amount of total heavy minerals in the Group I than in the Group II soils, Figure 1.
- (2) The higher organic matter content in the B horizons of the Group I than in the Group II soils, Table 2.
- (3) The greater quantity of calcium and magnesium minerals in the Group I than in the Group II soils, Figures 11 to 16.
- (4) The greater quantity of dark green hornblende in the C than in the B horizons of all soils, Figures 11 and 12.
- (5) The greater decomposition of dark green hornblende in the B than in the A horizon, Figures 11 and 12.
- (6) A similarity of nutrient delivery in the C horizons of all soils, Figure 17 and Plate 2.
- (7) A variable yet greater amount of nutrient delivery in the B than in the C horizons of all soils, Figure 17 and Plates 1 and 2.
- (8) A greater organic than inorganic base exchange capacity of the soil; a dominance of the calcium and magnesium cations in the organic exchange complex, the results of Tedrow and Gillam (38). Also, a higher

organic exchange capacity of the B horizon of the Group I soils (represented by Kalkaska and Emmet) than for the Group II soils (represented by Rubicon).

These data indicate that organic matter greatly assisted the decomposition of the heavy minerals, particularly the dark green hornblende in the fine sand fraction. The magnitude of this decomposition varied with the amount and type of organic matter. The presence of relatively high amounts of heavy minerals without organic matter did not provide sufficient plant nutrient delivery.

SUMMARY AND CONCLUSIONS

A study was made of the heavy minerals in the fine sand fraction of some Michigan podsoles. Detailed data obtained from petrographic observations, mechanical and chemical analyses, and Neubauer tests were correlated to indicate a type of soil weathering. A summation of the results and of the conclusions follows:

The brown B horizon of some Michigan podsoles was the result of a vigorous decomposition of a relatively high original content of the opaque and ferro-magnesian minerals.

Organic matter was an effective weathering agent of some heavy minerals in the B horizons.

The least resistant mineral to podsol weathering was dark green hornblende, followed by gray green hornblende, the opaque minerals, and the garnets.

The relative resistance to weathering varied within the profile. In general, the B horizons suffered a greater

decomposition of the heavy minerals than the A or C horizons.

The Kalkaska and Emmet soils (soils that support a hardwood cover) showed a greater amount of the calcium and magnesium heavy minerals in all horizons of the profile than the Wallace, Rubicon, Roselawn, and Grayling soils (soils that support a pine cover).

The Wallace sand showed marked differences in the microscopic count of heavy minerals from the other soils investigated.

A similar heavy mineral assemblage was found in the Group I (Wallace, Kalkaska, and Emmet) and Group II (Rubicon, Roselawn, Grayling, and Eastport) soils, although the quantity of heavy minerals was lower in the Group II soils.

Quantitative data on the heavy minerals were difficult to secure. More accurate results were obtained by subjecting the entire rather than a small part of the fine sand fraction to heavy mineral analyses.

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Table 1--Content of Free Alumina, Iron Oxide, and Colloidal Silica in the B Horizons.

Soil	Percent in Organic Free Soil		
	Alumina	Iron Oxide	Colloidal Silica
<u>GROUP I</u>			
Wallace sand	0.72	0.32	0.10
Kalkaska sand	0.30	0.33	0.04
Emmet sand	0.07	0.31	0.15
<u>GROUP II</u>			
Rubicon sand	0.68	0.25	0.20
Roselawn sand	0.36	0.30	0.12
Grayling sand	0.57	0.30	0.11
Eastport sand	0.09	0.10	0.03

Table 2--Mechanical Analyses, Content of Organic Matter, and pH of
Some Michigan Podsol Soils.

Soil Type and Horizon	Percent of Organic Matter	<u>Percent of Separates in Organic Free Soil</u>			pH	
		Sand (2.0-0.02mm)	Silt (0.02-0.002mm)	Clay (less than 0.002mm)		
<u>GROUP I</u>						
Wallace sand	A	2.0	96.2	2.3	1.0	6.5
	B	0.8	96.4	0.6	0.9	5.5
	C	---	98.4	0.8	---	6.5
Kalkaska sand	A	2.8	96.5	1.7	1.4	6.0
	B	0.8	94.9	2.3	1.0	4.8
	C	---	98.1	1.4	---	6.0
Emmet sand	A	2.5	95.7	2.0	1.2	6.3
	B	0.4	96.0	1.7	1.0	6.2
	C	---	98.3	1.2	---	8.0
<u>GROUP II</u>						
Rubicon sand	A	1.7	98.4	1.0	0.6	7.0
	B	0.1	97.1	0.5	0.1	6.0
	C	---	100.1	0.5	---	7.0
Roselawn sand	A	1.8	98.1	1.1	0.7	6.6
	B	0.1	97.1	0.7	0.5	5.7
	C	---	99.7	0.6	---	6.6
Grayling sand	A	1.9	98.5	1.0	0.7	6.3
	B	0.2	97.5	0.6	0.7	5.3
	C	---	99.7	0.6	---	6.3
Eastport sand	A	1.1	99.6	0.9	0.1	6.2
	B	0.1	99.4	0.3	---	6.8
	C	---	100.1	0.3	---	6.4

Table 3--Heavy Mineral Count of Brown, Pink, and Colorless Garnet in the Group I Soils.

Mineral and Horizon		Number of Particles in Various Horizons							
		Maximum cross-sectional area							
		0.25	0.5	1.0	2.0	3.0	4.0	6.0	10.0
<u>Wallace sand</u>									
Brown Garnet	A	--	2	154	82	22	26	14	--
	B	--	22	12	22	6	8	6	--
	C	--	6	109	92	32	32	19	--
Pink Garnet	A	--	--	74	86	16	4	4	--
	B	--	12	12	8	6	4	--	--
	C	--	--	16	77	38	19	12	--
Colorless Garnet	A	--	--	168	104	18	18	6	10
	B	--	20	16	18	2	2	6	10
	C	--	--	70	22	6	10	19	22
<u>Kalkaska sand</u>									
Brown Garnet	A	--	39	61	74	80	30	13	--
	B	--	2	12	26	14	20	24	2
	C	--	--	24	62	38	70	19	--
Pink Garnet	A	--	--	39	26	22	19	19	--
	B	--	--	12	36	56	22	16	--
	C	--	--	--	48	14	14	5	5
Colorless Garnet	A	--	37	24	4	6	--	--	--
	B	--	--	4	2	2	2	2	2
	C	--	7	67	65	14	24	2	--
<u>Emmet sand</u>									
Brown Garnet	A	--	--	38	59	13	34	15	--
	B	--	--	8	12	12	4	--	--
	C	--	--	--	--	6	19	14	3
Pink Garnet	A	--	4	55	84	15	11	17	--
	B	--	--	2	6	8	10	12	--
	C	--	--	--	3	3	6	10	--
Colorless Garnet	A	--	6	23	23	2	4	4	--
	B	--	--	2	10	4	--	2	--
	C	--	--	--	10	6	14	17	--

Table 4--Heavy Mineral Count of Brown, Pink, and Colorless Garnet in the Group II Soils.

Mineral and Horizon		Number of Particles in Various Horizons							
		Maximum cross-sectional area							
		0.25	0.5	1.0	2.0	3.0	4.0	6.0	10.0
<u>Rubicon sand</u>									
Brown Garnet	A	--	51	26	27	6	16	8	--
	B	--	10	2	2	2	6	2	6
	C	--	--	3	14	2	26	21	--
Pink Garnet	A	--	80	45	30	8	11	2	--
	B	--	--	2	2	4	--	--	--
	C	--	--	3	11	6	26	11	--
Colorless Garnet	A	--	--	15	5	1	1	--	--
	B	--	--	2	2	2	--	--	4
	C	--	--	3	3	--	5	--	--
<u>Roselawn sand</u>									
Brown Garnet	A	--	--	10	30	6	29	11	--
	B	--	--	--	--	22	4	2	4
	C	--	--	5	14	8	19	5	10
Pink Garnet	A	--	--	1	10	4	10	4	--
	B	--	--	--	6	12	8	2	10
	C	--	--	1	10	6	6	5	--
Colorless Garnet	A	--	--	7	34	2	7	5	--
	B	--	--	--	--	4	--	--	2
	C	--	1	5	8	3	6	1	6
<u>Grayling sand</u>									
Brown Garnet	A	--	15	45	20	6	2	1	--
	B	--	--	--	--	2	4	2	2
	C	--	--	1	3	7	17	9	--
Pink Garnet	A	--	7	26	10	8	8	8	--
	B	--	--	--	--	4	2	2	2
	C	--	--	--	7	5	21	13	--
Colorless Garnet	A	--	2	8	8	5	--	--	--
	B	--	--	--	2	2	2	--	2
	C	--	--	--	--	--	2	--	--
<u>Eastport sand</u>									
Brown Garnet	A	--	65	18	22	3	7	3	--
	B	--	--	--	--	2	2	--	--
	C	--	--	7	42	11	59	18	--
Pink Garnet	A	--	13	1	--	--	--	--	--
	B	--	--	--	--	--	--	--	--
	C	--	--	4	24	20	9	7	--
Colorless Garnet	A	--	4	3	1	--	--	--	--
	B	--	--	--	--	2	--	--	--
	C	--	2	31	53	7	2	--	--

Table 5--Heavy Mineral Count of the Opaque Minerals.

Soil Type and Horizon		Number of Particles in Various Horizons							
		Maximum cross-sectional area							
		0.25	0.5	1.0	2.0	3.0	4.0	6.0	10.0
<u>GROUP I SOILS</u>									
Wallace sand	A	--	46	890	172	18	22	--	--
	B	--	60	150	108	36	20	2	2
	C	--	--	589	624	240	29	--	--
Kalkaska sand	A	--	74	398	178	19	7	4	--
	B	--	70	362	406	178	138	36	28
	C	--	--	232	475	103	50	7	24
Emmet sand	A	--	3	567	399	147	19	8	11
	B	--	26	112	200	40	52	30	24
	C	--	--	446	143	666	110	39	28
<u>GROUP II SOILS</u>									
Rubicon sand	A	--	430	368	60	7	20	4	--
	B	--	82	10	32	18	22	26	--
	C	--	--	8	53	27	47	24	--
Roselawn sand	A	--	7	116	275	40	28	7	5
	B	--	60	54	118	58	78	12	2
	C	--	25	75	50	8	11	8	6
Grayling sand	A	--	--	83	102	35	15	--	--
	B	--	4	24	60	26	60	10	8
	C	--	--	--	86	26	95	25	7
Eastport sand	A	--	39	13	25	39	1	10	7
	B	--	--	--	2	16	20	16	24
	C	--	22	271	341	13	26	15	--

Table 6--Heavy Mineral Count of Dark Green Hornblende, Gray Green Hornblende, and Epidote in the Group I Soils.

Mineral and Horizon		Number of Particles in Various Horizons							
		Maximum cross-sectional area							
		0.25	0.5	1.0	2.0	3.0	4.0	6.0	10.0
<u>Wallace sand</u>									
Dark Green Hornblende	A	--	96	524	72	34	28	4	2
	B	--	474	496	88	38	32	8	4
	C	--	--	1216	608	246	19	10	13
Gray Green Hornblende	A	--	4	150	12	18	12	10	2
	B	--	230	252	114	60	66	30	4
	C	--	--	77	10	32	16	16	6
Epidote	A	--	4	318	30	10	4	--	--
	B	--	22	18	18	8	2	2	--
	C	--	--	400	176	35	16	--	--
<u>Kalkaska sand</u>									
Dark Green Hornblende	A	185	1684	120	50	24	17	19	19
	B	--	56	264	208	160	64	58	28
	C	--	96	1138	1238	86	202	53	31
Gray Green Hornblende	A	1018	2405	26	20	19	--	--	15
	B	--	32	464	102	66	42	12	18
	C	--	12	298	120	34	14	5	19
Epidote	A	--	37	13	15	19	11	6	6
	B	--	2	28	36	28	10	6	2
	C	--	5	43	17	14	14	5	2
<u>Emmet sand</u>									
Dark Green Hornblende	A	--	65	1166	935	63	179	197	21
	B	--	68	198	136	56	32	26	10
	C	--	--	83	138	33	396	536	193
Gray Green Hornblende	A	--	53	1109	113	4	53	29	--
	B	--	46	300	178	192	106	24	10
	C	--	--	--	110	110	28	17	19
Epidote	A	--	4	65	69	2	27	11	--
	B	--	--	10	20	16	10	--	--
	C	--	--	--	3	3	28	17	6

Table 7--Heavy Mineral Count of Dark Green Hornblende, Gray Green Hornblende, and Epidote in the Group II Soils.

Mineral and Horizon		Number of Particles in Various Horizons							
		Maximum cross-sectional area							
		0.25	0.5	1.0	2.0	3.0	4.0	6.0	10.0
<u>Rubicon sand</u>									
Dark Green Hornblende	A	--	455	141	131	15	29	14	5
	B	--	152	22	14	20	28	32	20
	C	--	5	59	105	5	161	140	23
Gray Green Hornblende	A	--	281	37	16	4	7	2	--
	B	--	330	16	10	12	10	--	8
	C	--	11	59	36	5	57	11	11
Epidote	A	--	122	151	23	6	7	--	--
	B	--	--	--	--	--	--	4	--
	C	--	--	11	21	6	26	27	--
<u>Roselawn sand</u>									
Dark Green Hornblende	A	--	20	119	292	22	52	15	2
	B	--	200	102	110	46	96	12	6
	C	--	--	200	269	40	90	20	
Gray Green Hornblende	A	--	7	53	26	4	2	2	1
	B	--	240	46	78	130	100	6	--
	C	--	25	64	3	--	1	13	6
Epidote	A	--	4	51	30	4	9	5	5
	B	--	--	2	12	10	8	4	--
	C	--	3	25	38	4	1	3	9
<u>Grayling sand</u>									
Dark Green Hornblende	A	--	68	230	95	10	30	8	15
	B	--	14	314	100	16	18	56	3
	C	--	3	3	34	18	107	88	26
Gray Green Hornblende	A	--	10	32	80	9	7	8	3
	B	--	8	48	34	30	60	10	14
	C	--	--	8	16	3	47	23	4
Epidote	A	--	--	115	59	20	11	7	4
	B	--	--	--	--	6	4	2	2
	C	--	--	--	13	18	23	13	8
<u>Eastport sand</u>									
Dark Green Hornblende	A	130	783	364	131	55	39	8	26
	B	--	2	--	8	16	10	26	46
	C	--	48	359	251	42	42	22	--
Gray Green Hornblende	A	780	2769	546	46	4	4	--	14
	B	--	2	10	--	18	34	18	34
	C	--	7	59	40	2	--	--	--
Epidote	A	--	7	10	3	5	11	2	--
	B	--	--	--	--	2	4	8	--
	C	--	--	51	37	13	18	--	--

Table 8--Heavy Mineral Count of the Minor Minerals: Tremolite, Zircon, Muscovite, and Tourmaline in the Group I Soils.

Mineral and Horizon		Number of Particles in Various Horizons							
		Maximum cross-sectional area							
		0.25	0.5	1.0	2.0	3.0	4.0	6.0	10.0
<u>Wallace sand</u>									
Tremolite	A	--	--	34	2	--	--	--	--
	B	--	--	--	2	2	2	2	--
	C	--	--	6	--	--	--	3	--
Zircon	A	--	--	20	10	--	2	2	--
	B	--	290	150	34	12	8	4	10
	C	--	3	22	10	--	3	3	--
Muscovite	A	--	--	30	10	--	--	--	--
	B	--	--	--	--	--	--	--	--
	C	--	3	32	--	--	--	--	--
Tourmaline	A	--	--	6	--	--	--	--	--
	B	--	50	10	--	--	--	--	--
	C	--	3	--	--	--	--	--	--
<u>Kalkaska sand</u>									
Tremolite	A	--	9	--	2	6	--	2	2
	B	--	8	30	12	8	4	--	--
	C	--	--	--	9	--	--	--	2
Zircon	A	--	9	6	6	15	6	4	--
	B	--	12	46	84	44	36	22	10
	C	--	--	13	2	5	5	2	--
Muscovite	A	--	33	24	--	--	--	--	--
	B	--	--	--	--	--	--	--	--
	C	--	--	7	7	--	--	--	--
Tourmaline	A	--	19	2	2	--	--	--	--
	B	--	6	8	--	2	--	--	--
	C	--	2	5	2	--	--	--	--
<u>Emmet sand</u>									
Tremolite	A	--	--	11	6	--	6	--	--
	B	--	--	2	6	2	6	--	--
	C	--	--	--	--	--	--	--	--
Zircon	A	--	--	6	--	--	--	--	--
	B	--	4	20	14	14	--	10	--
	C	--	--	--	--	3	3	--	--
Muscovite	A	--	4	13	6	4	6	--	--
	B	--	--	--	--	--	--	--	--
	C	--	--	--	6	--	6	8	--
Tourmaline	A	--	6	8	--	--	--	--	--
	B	--	--	2	--	--	--	--	--
	C	--	--	--	--	--	--	--	--

Table 9--Heavy Mineral Count of the Minor Minerals: Tremolite, Zircon, Muscovite, and Tourmaline in the Group II Soils.

Mineral and Horizon	Number of Particles in Various Horizons							
	Maximum cross-sectional area							
	0.25	0.5	1.0	2.0	3.0	4.0	6.0	10.0
<u>Rubicon sand</u>								
Tremolite	A	--	2	3	4	--	--	--
	B	--	--	--	--	2	--	--
	C	--	--	2	6	2	8	2
Zircon	A	--	1	2	3	2	1	--
	B	--	30	--	6	10	6	4
	C	--	--	--	--	2	--	--
Muscovite	A	--	--	5	9	--	--	1
	B	--	--	--	--	--	--	--
	C	--	--	2	2	2	2	--
Tourmaline	A	--	10	2	--	--	--	--
	B	--	--	--	--	2	--	--
	C	--	--	--	--	--	--	--
<u>Roselawn sand</u>								
Tremolite	A	--	--	1	3	--	--	--
	B	--	--	--	8	2	--	2
	C	--	--	3	--	--	--	--
Zircon	A	--	--	12	10	2	3	6
	B	--	2	6	8	4	2	--
	C	--	--	3	3	1	--	--
Muscovite	A	--	--	9	6	2	3	--
	B	--	--	--	--	--	--	--
	C	--	--	10	1	--	3	--
Tourmaline	A	--	--	3	--	--	--	--
	B	--	--	--	2	--	--	--
	C	--	--	--	--	--	--	--
<u>Grayling sand</u>								
Tremolite	A	--	--	--	--	--	--	--
	B	--	--	--	4	--	2	2
	C	--	--	--	--	--	--	3
Zircon	A	--	--	2	1	1	--	--
	B	--	--	2	--	--	2	--
	C	--	--	--	--	--	3	1
Muscovite	A	--	--	1	1	--	--	--
	B	--	--	2	--	--	--	--
	C	--	--	--	--	--	3	--
Tourmaline	A	--	--	--	--	--	--	--
	B	--	--	--	--	--	--	--
	C	--	--	--	--	--	--	--

Table 9(Cont.)

<u>Eastport sand</u>									
Tremolite	A	--	1	3	4	1	--	--	--
	B	--	--	--	--	--	--	--	4
	C	--	--	9	4	--	--	--	--
Zircon	A	--	7	8	8	5	--	--	--
	B	--	--	--	--	--	--	6	--
	C	--	--	4	2	--	--	--	--
Muscovite	A	--	52	20	20	--	13	--	--
	B	--	--	--	--	--	--	--	--
	C	--	--	2	2	--	--	--	--
Tourmaline	A	--	20	1	--	--	--	--	--
	B	--	--	--	--	--	--	--	--
	C	--	--	9	--	--	--	--	--

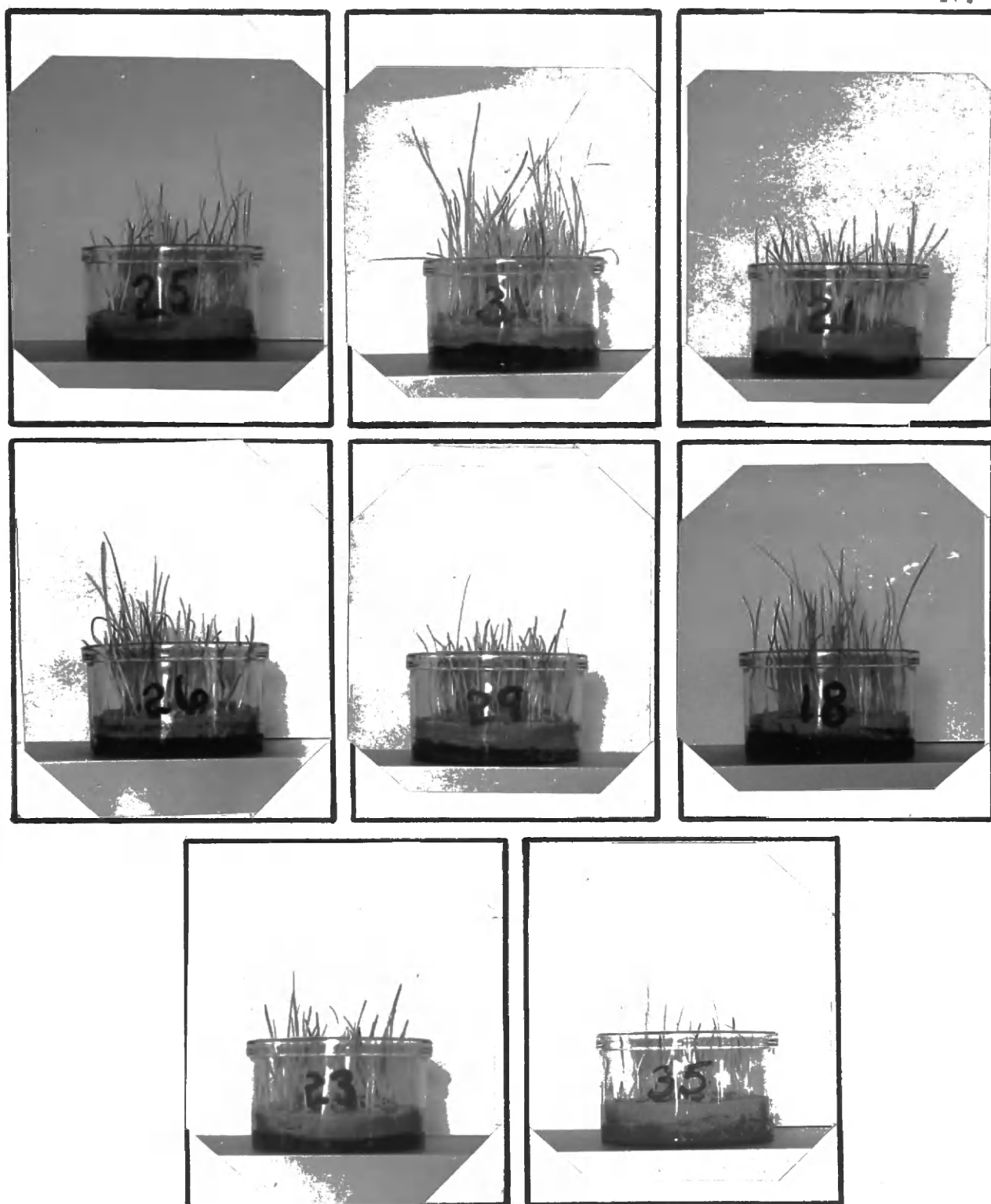


Plate 1. Neubauer tests on the B horizon of some Michigan podsoles.

Upper---	25 Kalkaska	31 Emmet	21 Wallace
Middle--	26 Grayling	29 Rubicon	18 Roselawn
Lower---	23 Eastport	35 Check	



Plate 2. Neubauer tests on the C horizon of some Michigan podzols.

1---Kalkaska
2---Emmet
3---Wallace
4---Check

5---Eastport
6---Roselawn
7---Rubicon
8---Grayling

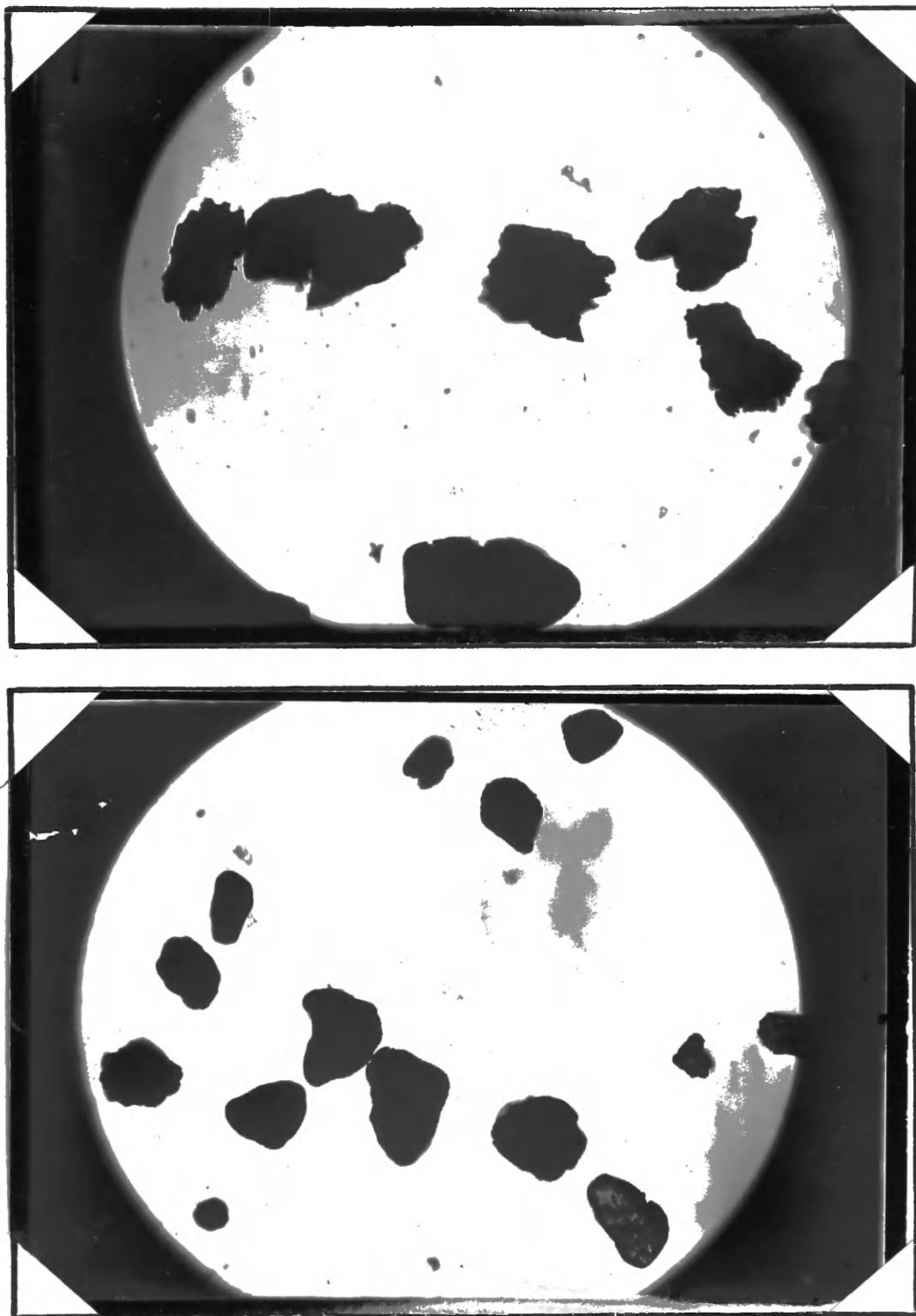


Plate 3. Photomicrographs of hornblende. 70X

Upper---severely weathered hornblende in the A horizon of the Kalkaska and Emmet sands.

Lower---slightly weathered hornblende in the A horizon of the Rubicon, Roselawn, Grayling, and Eastport sands.

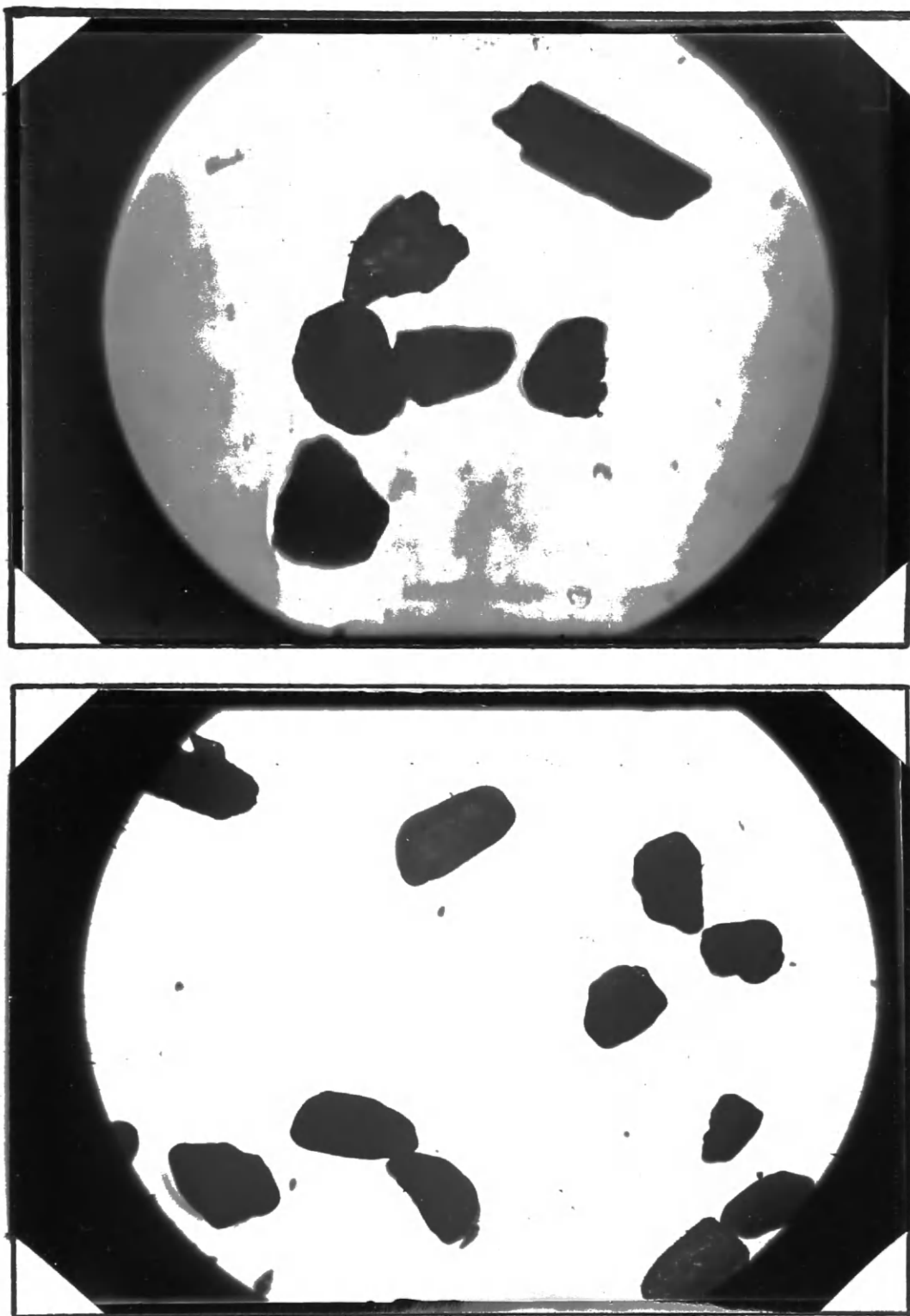


Plate 4. Photomicrographs of the heavy minerals of the C horizons. 70X

Upper---slightly altered heavy minerals of the Group I soils.

Lower---slightly altered heavy minerals of the Group II soils.

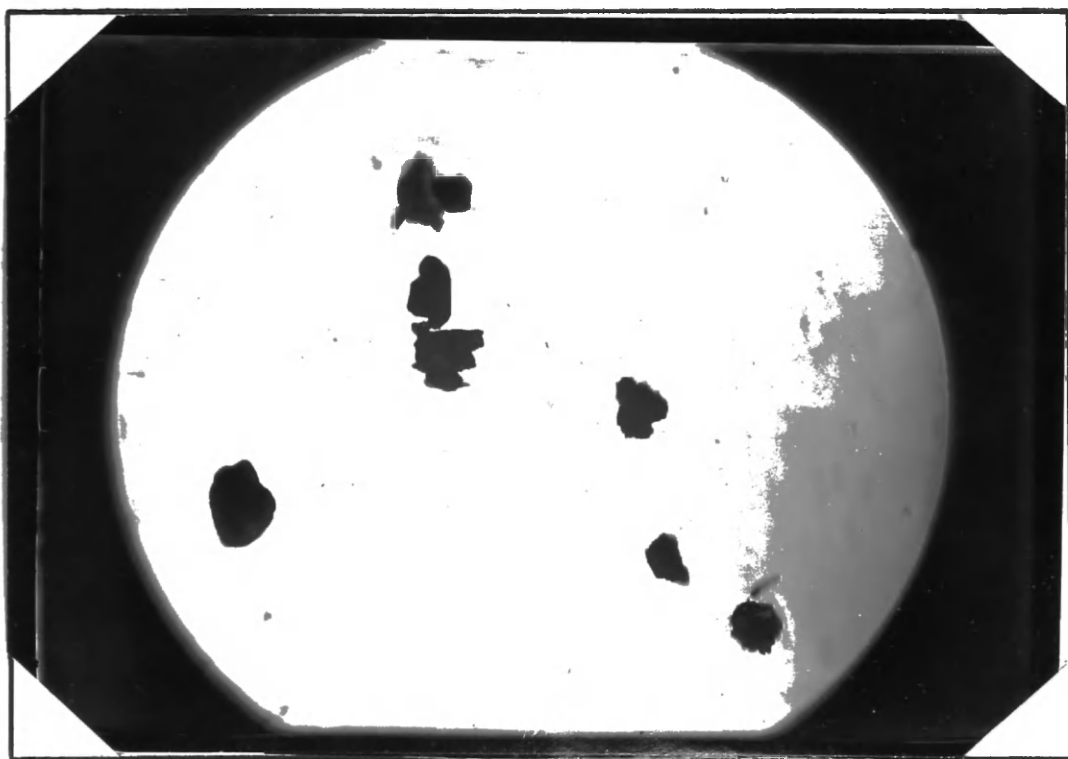
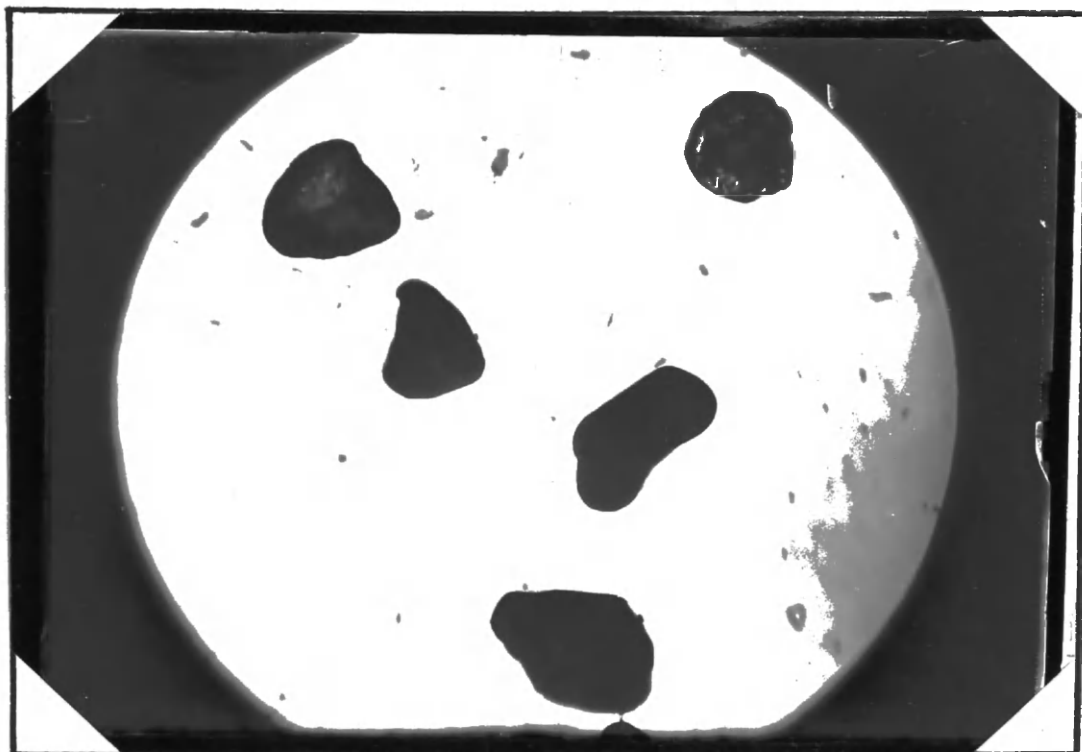


Plate 5. Photomicrographs of the heavy minerals. 70X
Upper---well-rounded grains characteristic of all
horizons of the Wallace sand.
Lower---small, irregular, wind-blown hornblende grains
in the A horizon of the Eastport sand.

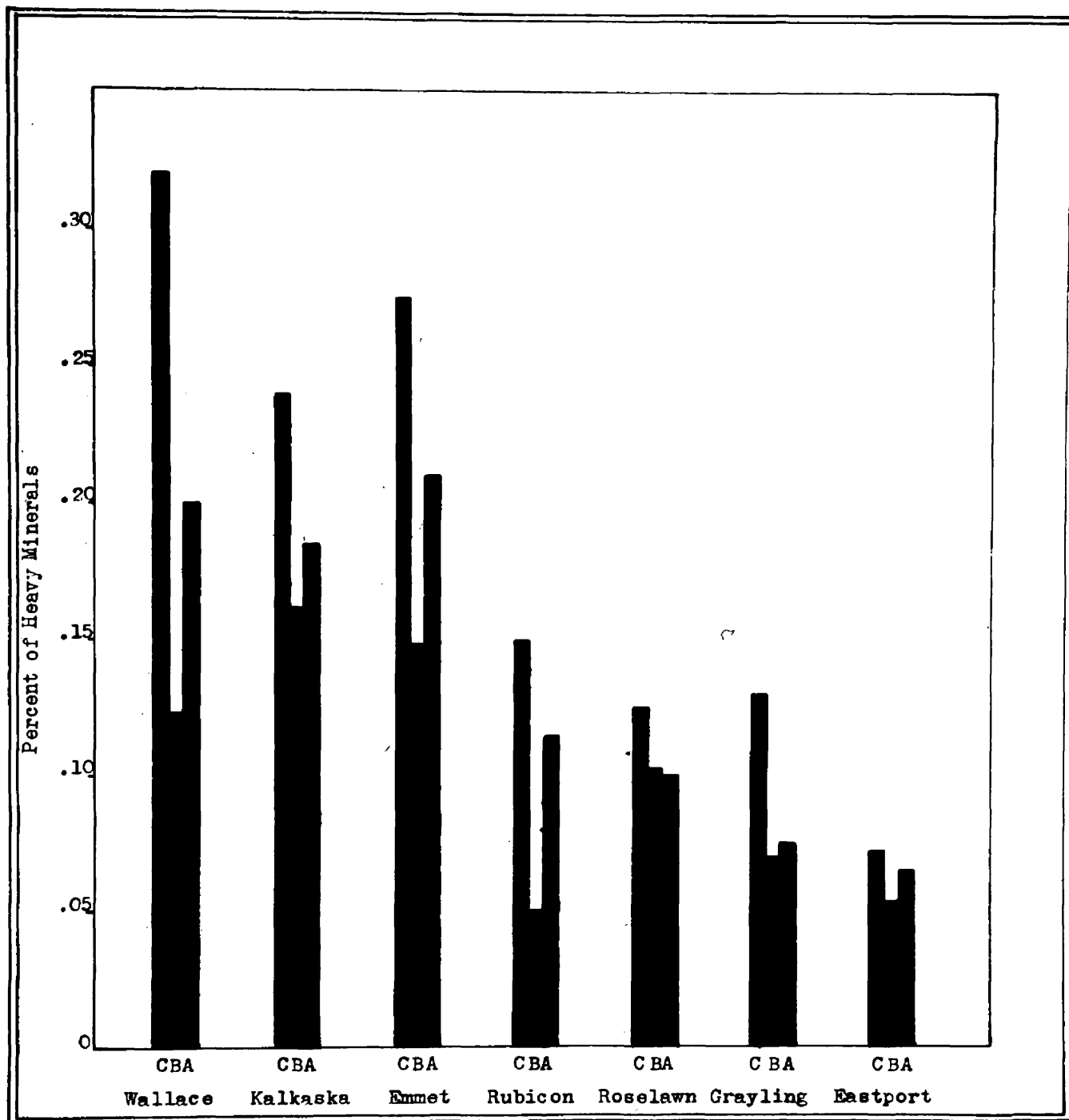


Figure 1. Percent of heavy minerals in the fine sand fraction of the Group I and II soils.
(20 grams of organic-free soil)

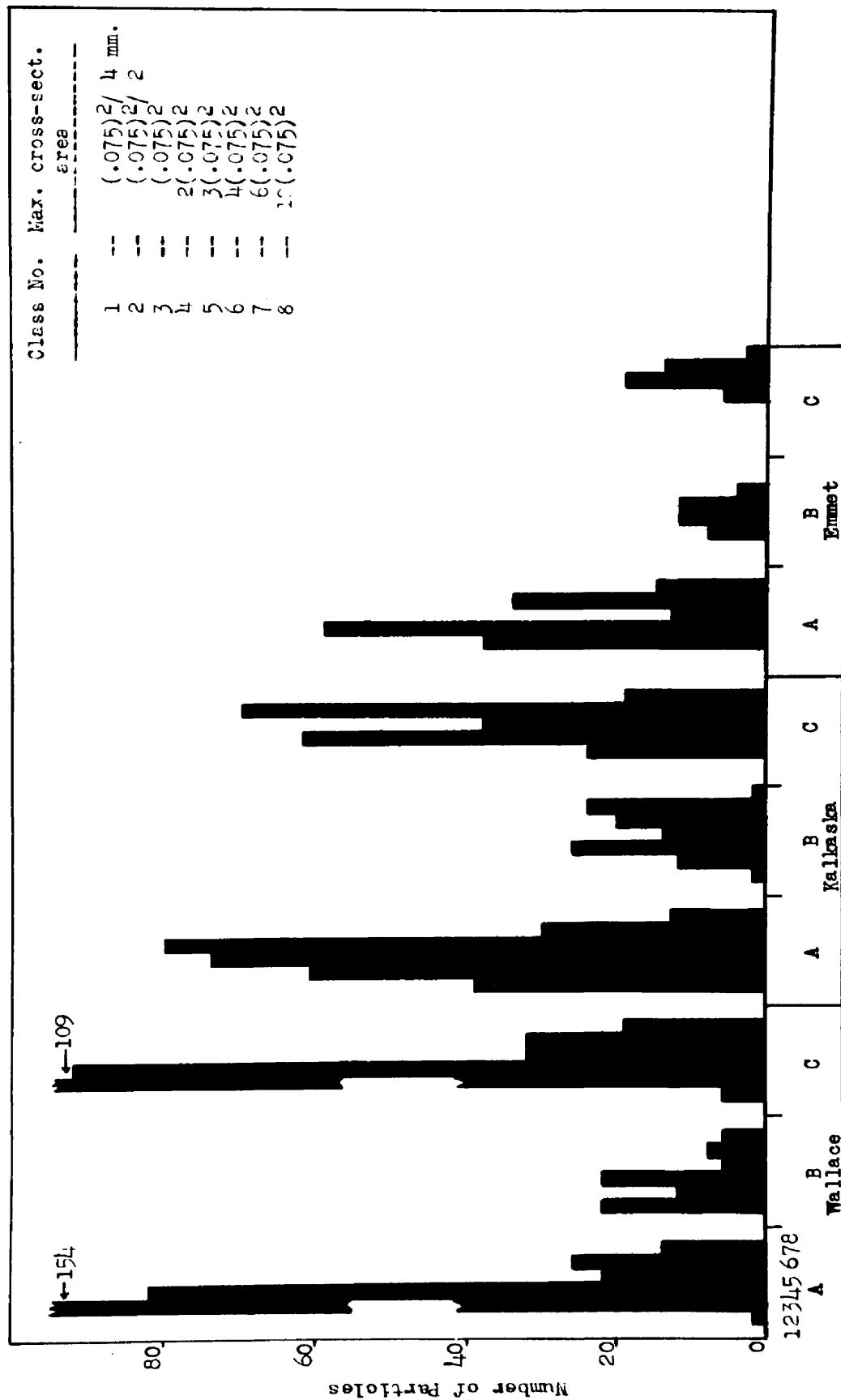


Figure 2. Microscopic count and grain size distribution of brown garnet in the fine sand fraction of the Group I soils.
(20 grams of organic-free soil)

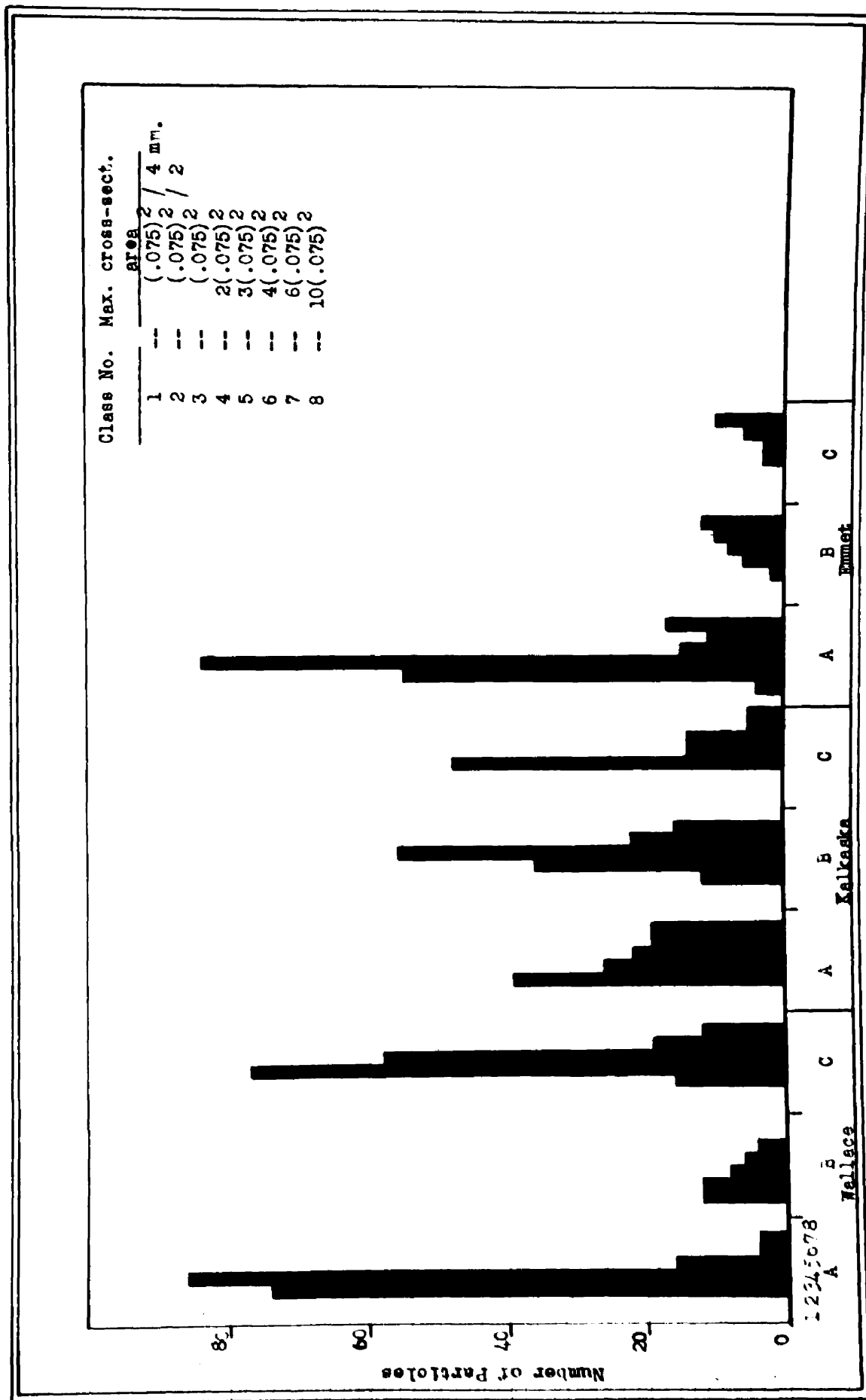


Figure 3. Microscopic count and grain size distribution of pink garnet in the fine sand fraction of the Group I soils. (20 grams of organic-free soil)

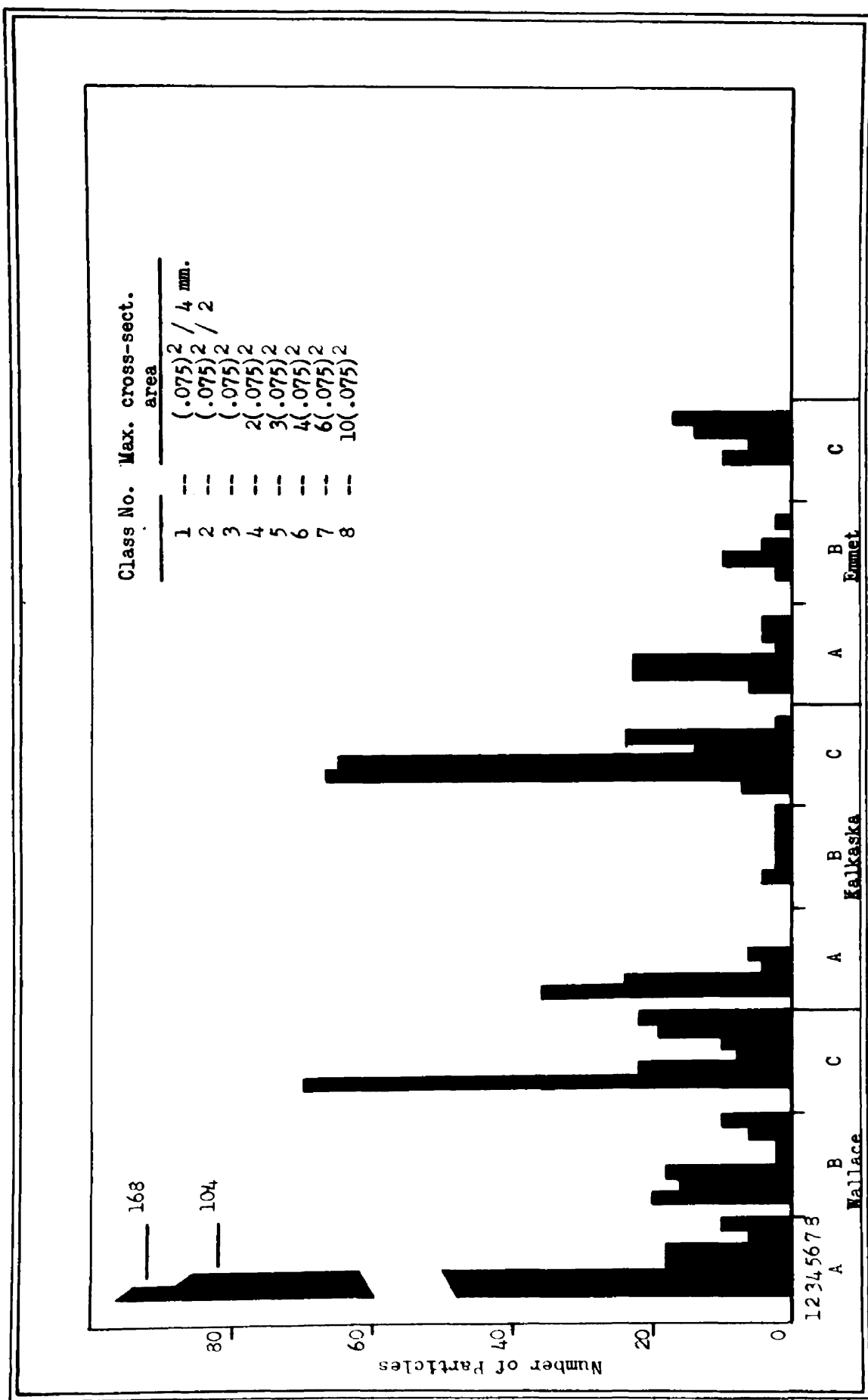


Figure 4. Microscopic count and grain size distribution of colorless garnet in the fine sand fraction of the Group I soils.
(20 grams of organic-free soil)

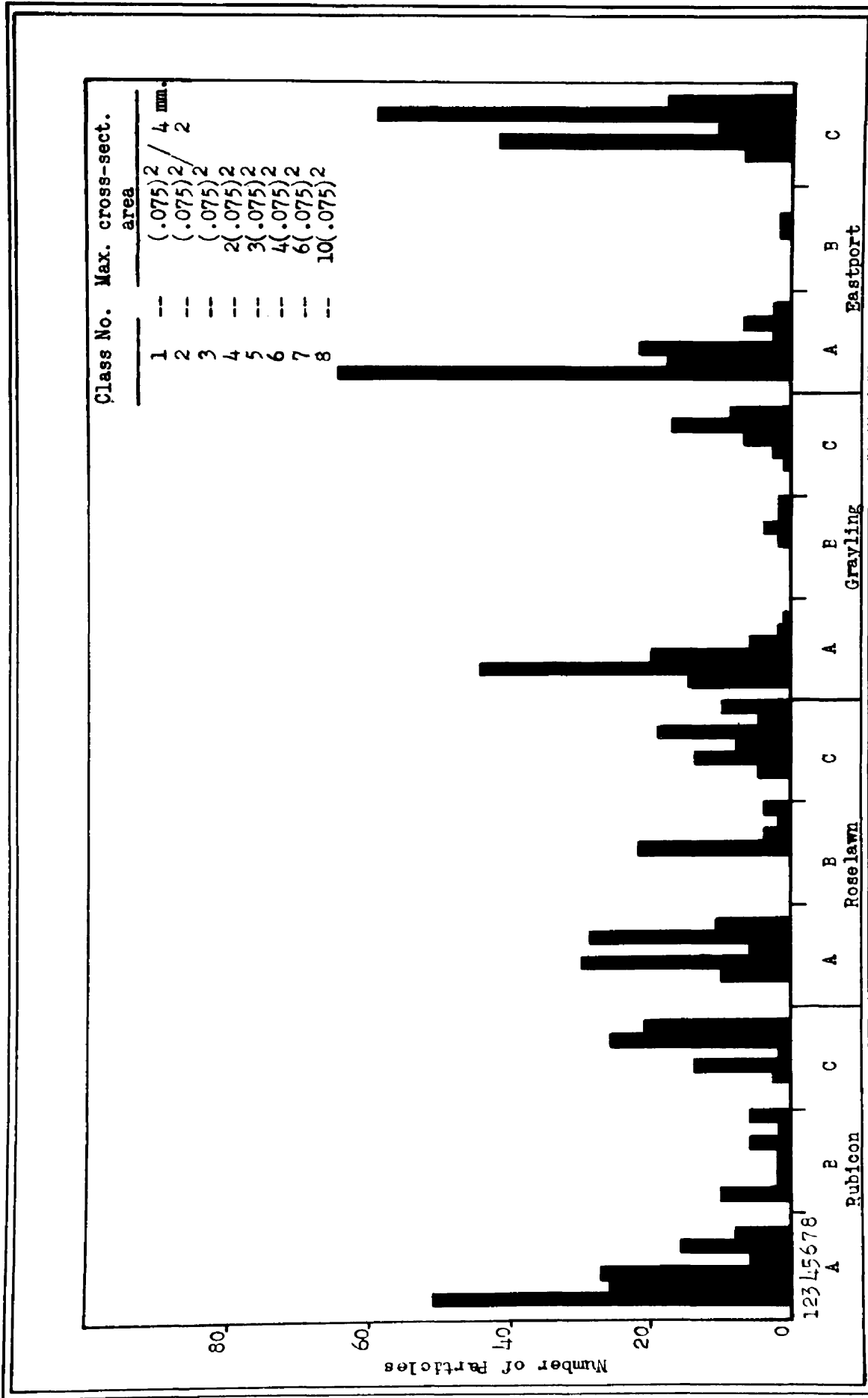


Figure 5. Microscopic count and grain size distribution of brown garnet in the fine sand fraction of the Group II soils.
(20 grams of organic-free soil)

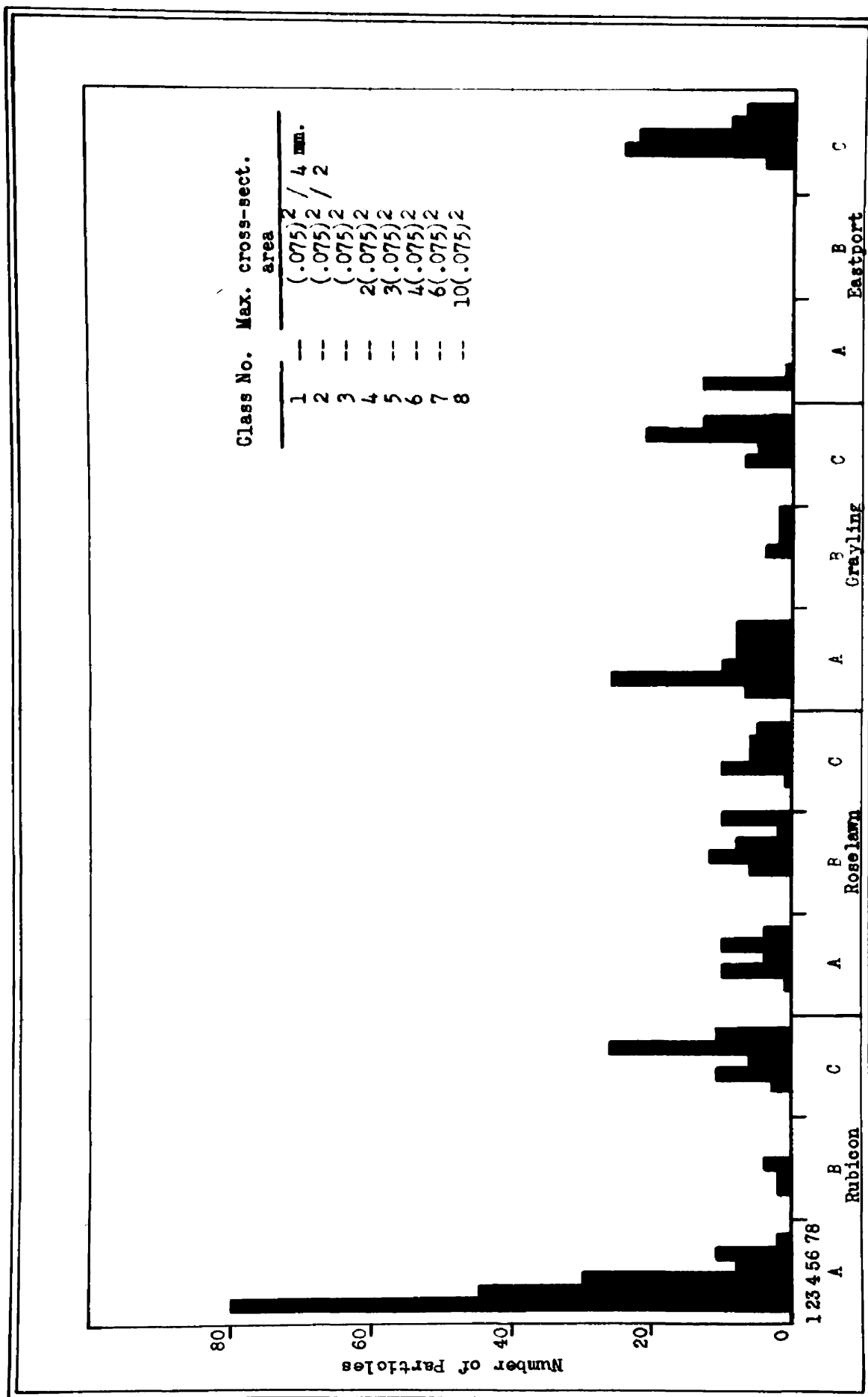


Figure 6. Microscopic count and grain size distribution of pink garnet in the fine sand fraction of the Group II soils. (20 grams of organic-free soil)

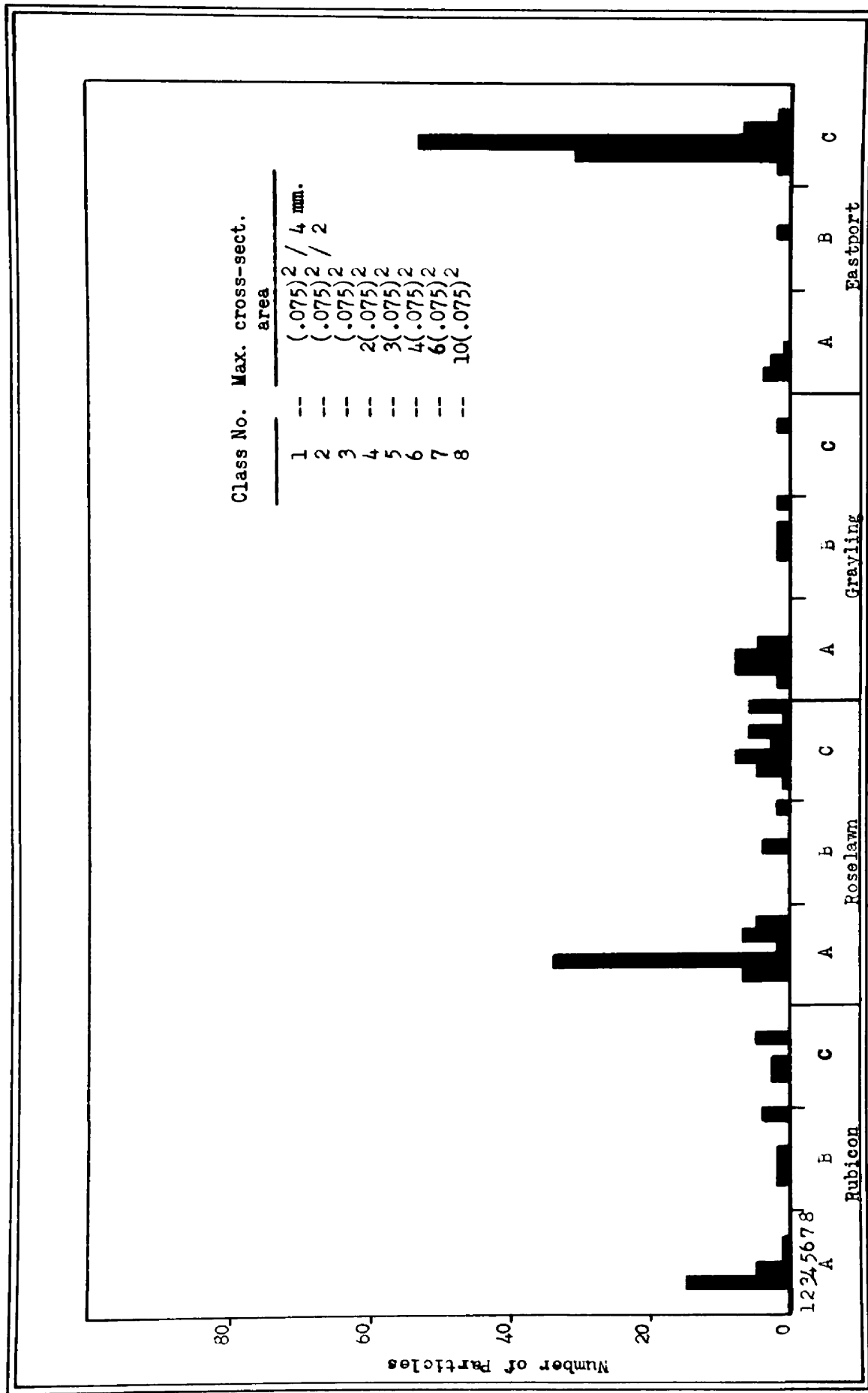


Figure 7. Microscopic count and grain size distribution of colorless garnet in the fine sand fraction of the Group II soils.
(20 grams of organic-free soil)

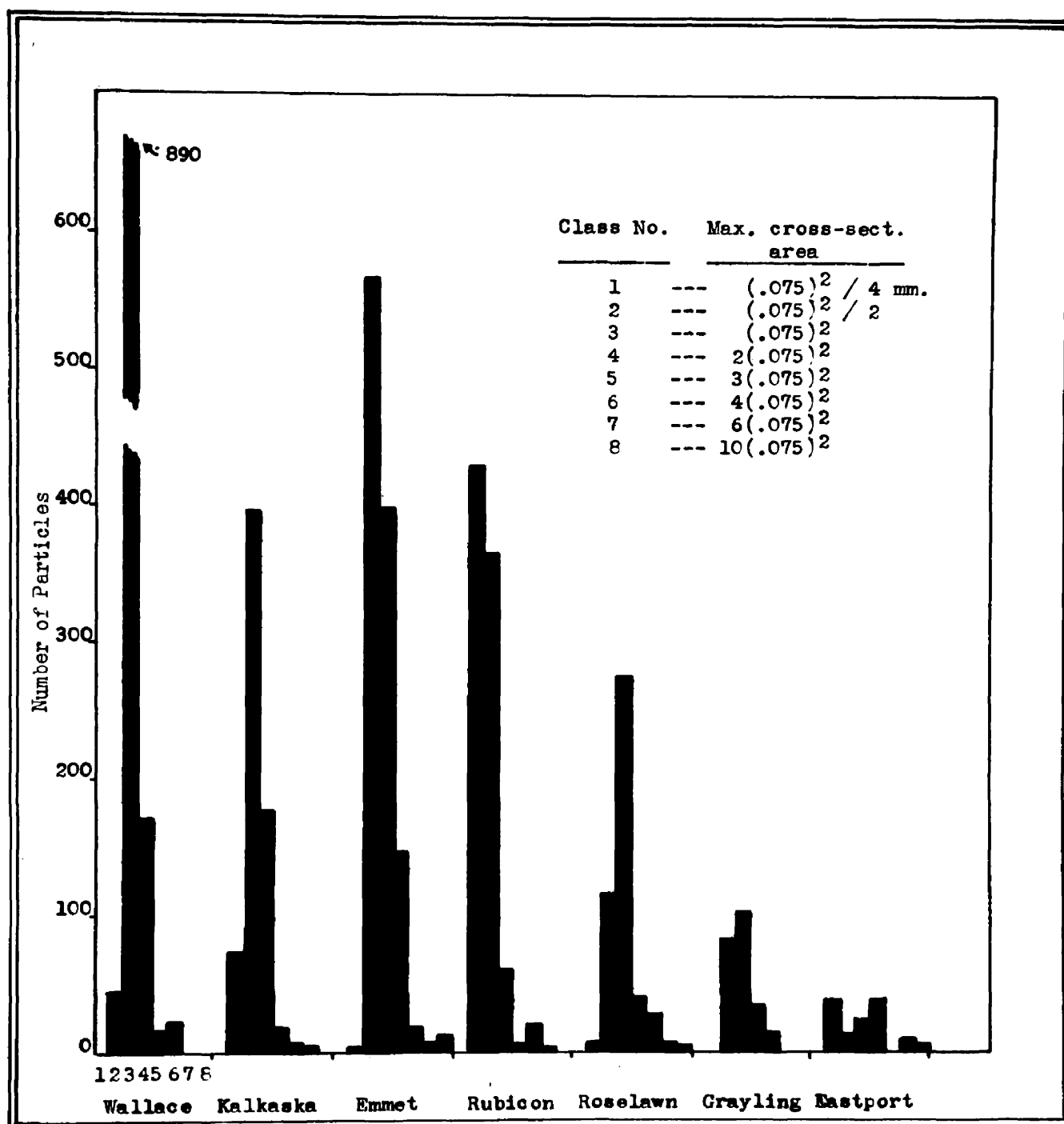


Figure 8. Microscopic count and grain size distribution of the opaque minerals in the fine sand fraction of the A horizon of the Group I and II soils. (20 grams of organic-free soil)

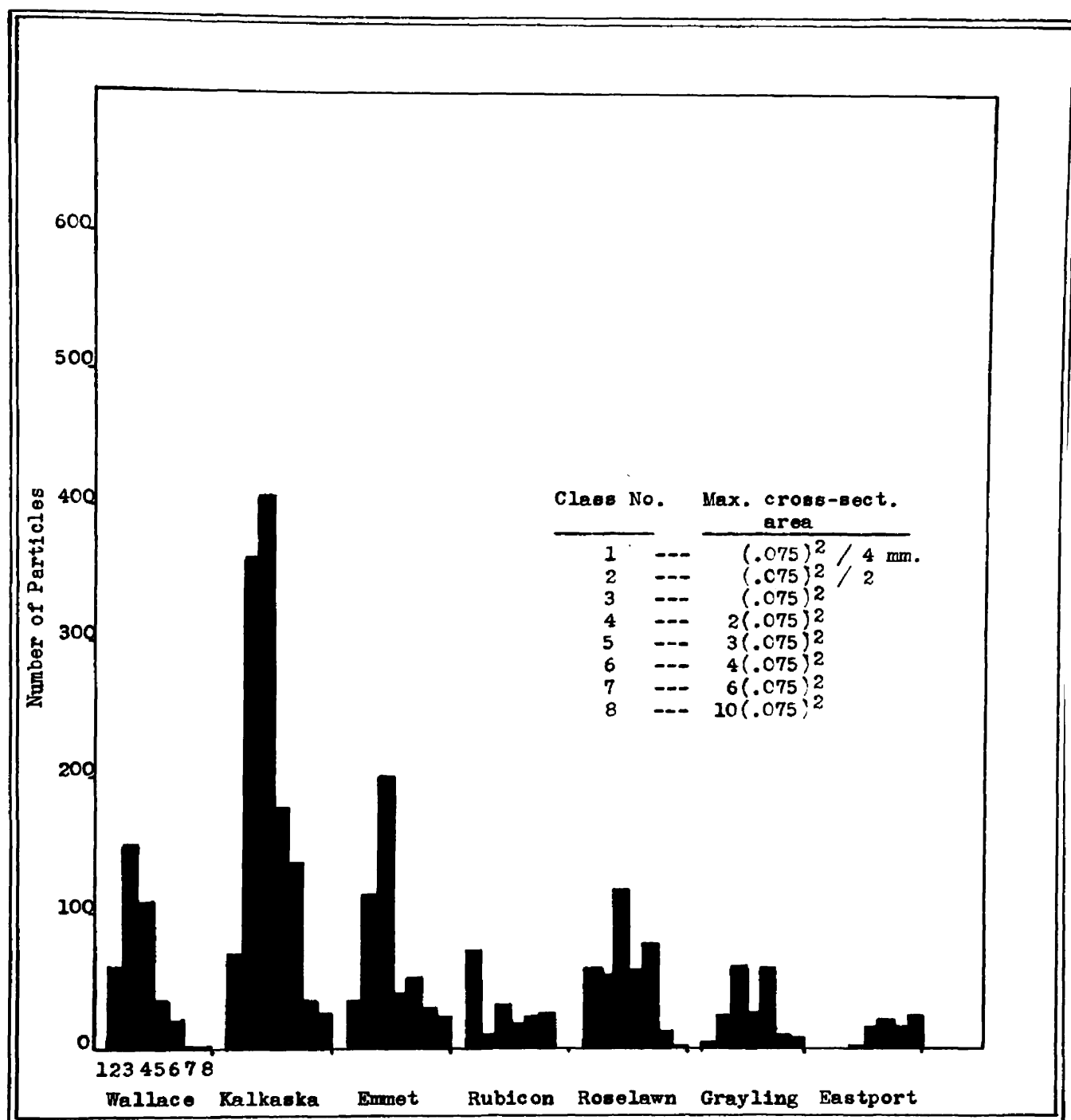


Figure 9. Microscopic count and grain size distribution of the opaque minerals in the fine sand fraction of the B horizon of the Group I and II soils.
(20 grams of organic-free soil)

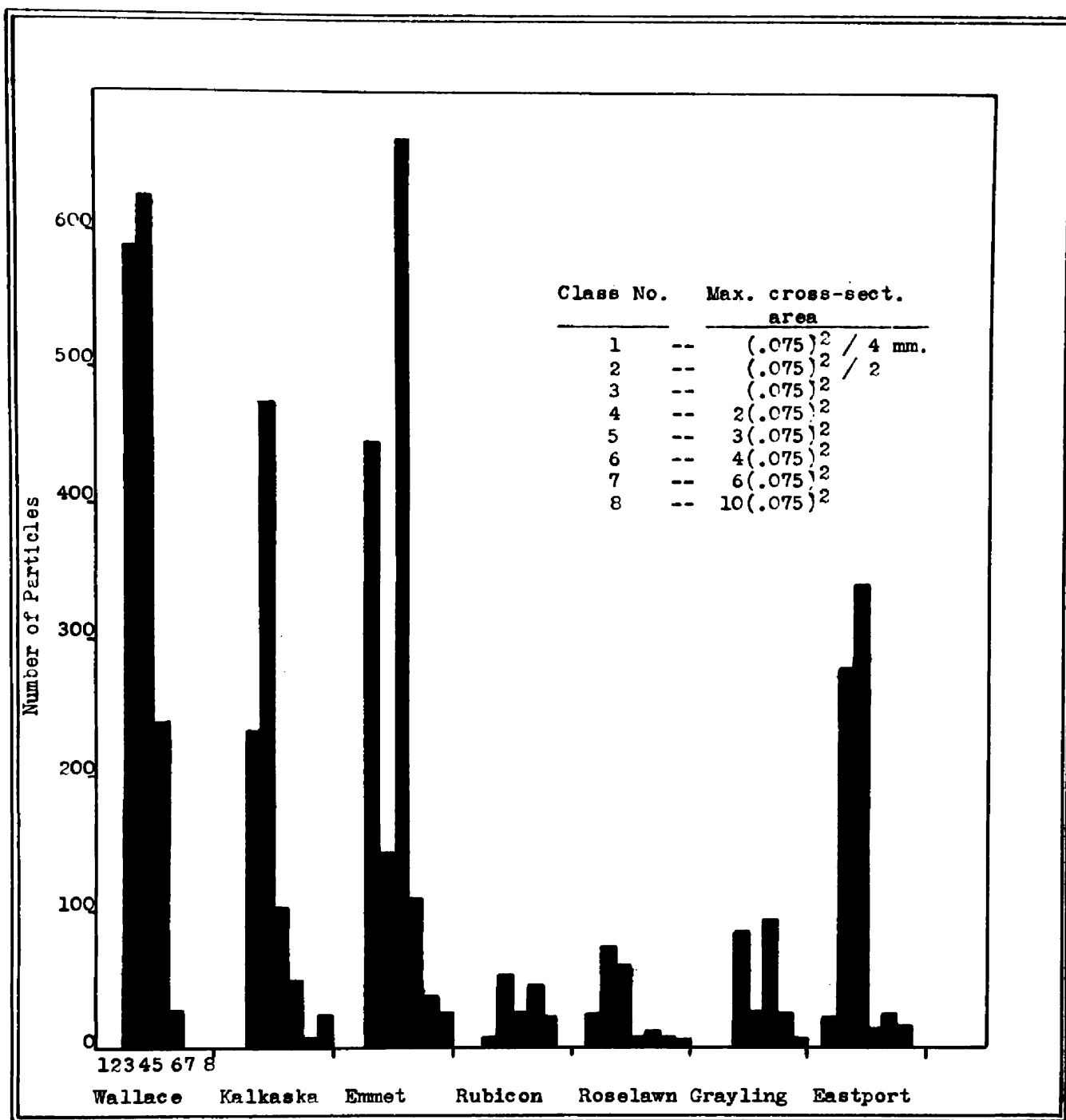


Figure 10. Microscopic count and grain size distribution of the opaque minerals in the fine sand fraction of the C horizon of the Group I and II soils.
(20 grams of organic-free soil)

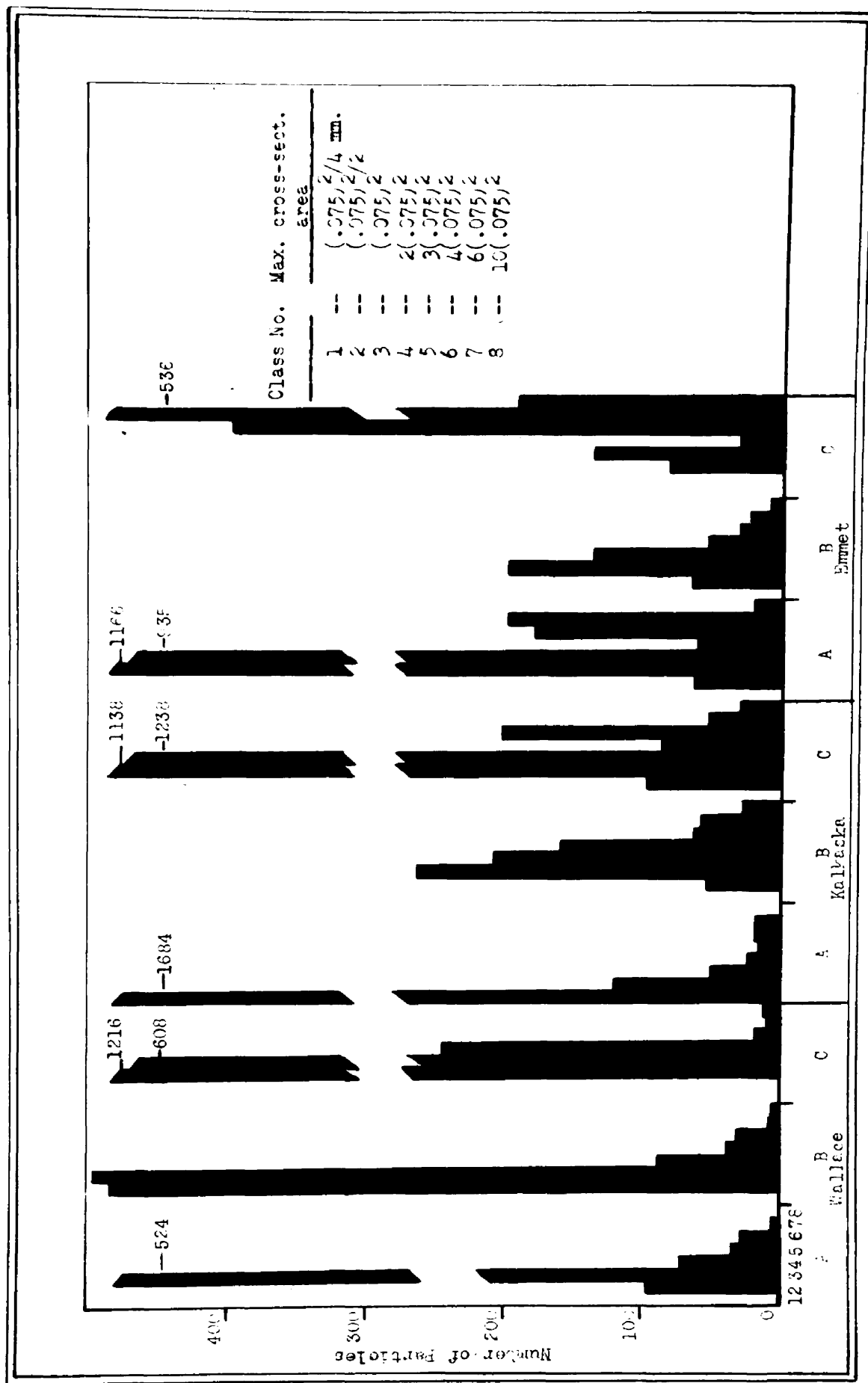


Figure 11. Microscopic count and grain size distribution of dark green hornblende in the fine sand fraction of the Group I soils.
(20 grams of organic-free soil)

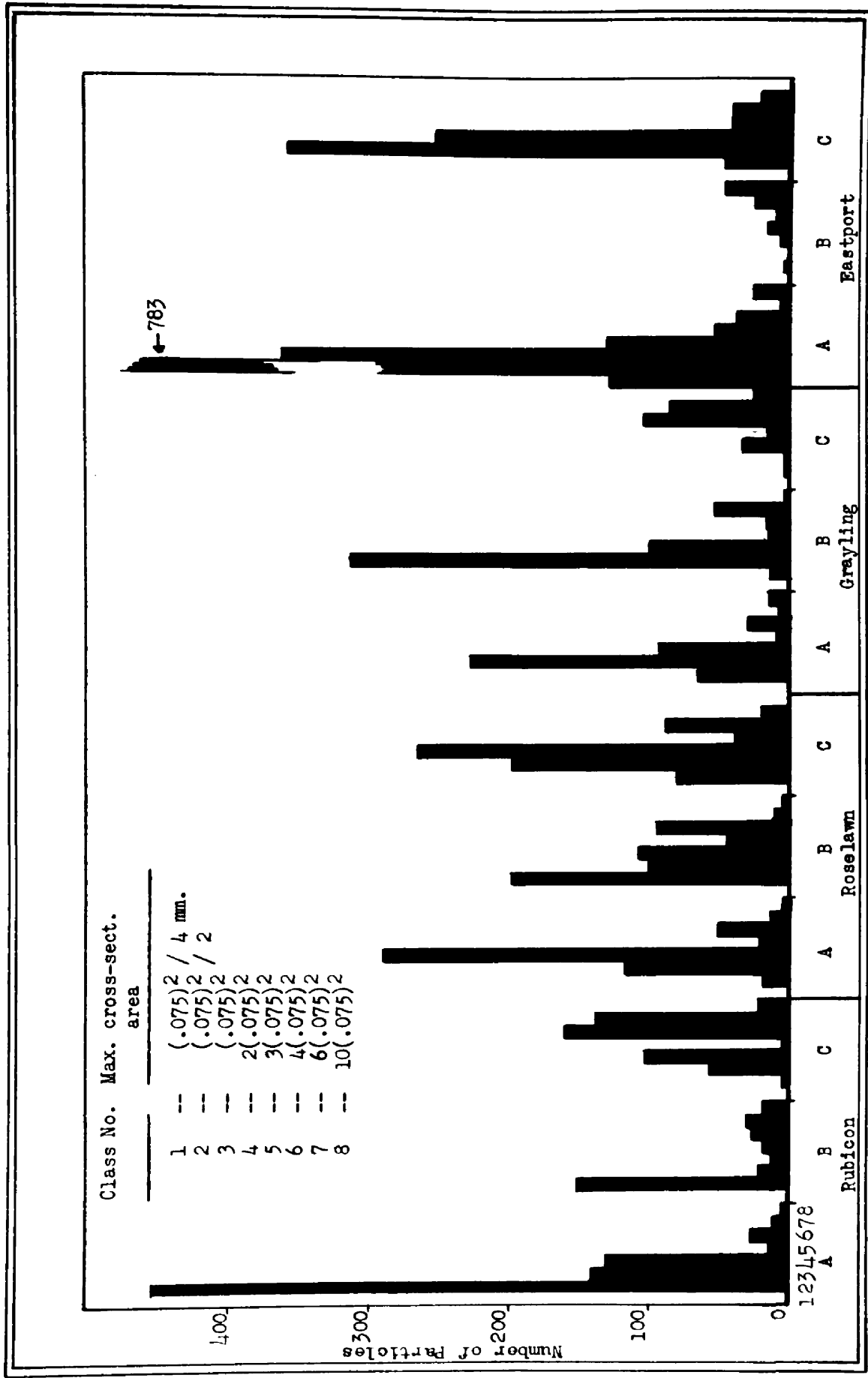


Figure 12. Microscopic count and grain size distribution of dark green hornblende in the fine sand fraction of Group II soils. (20 grams of organic-free soil)

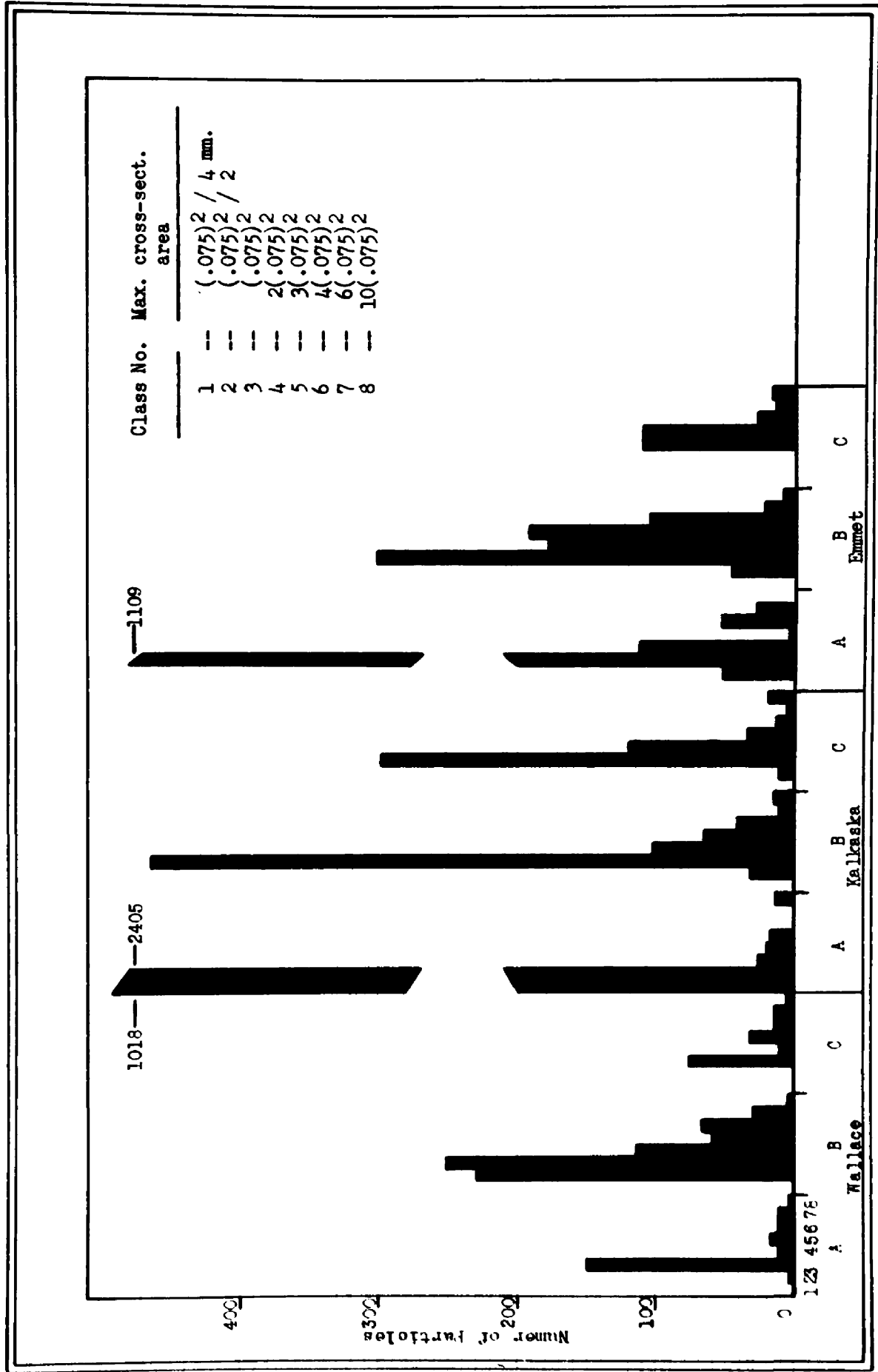
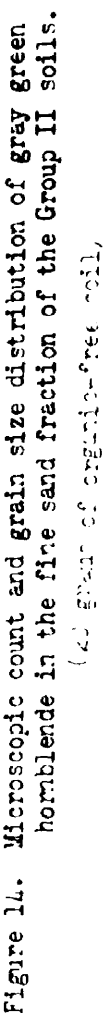


Figure 13. Microscopic count and grain size distribution of gray green hornblende in the fine sand fraction of the Group I soils. (20 grams of organic-free soil)



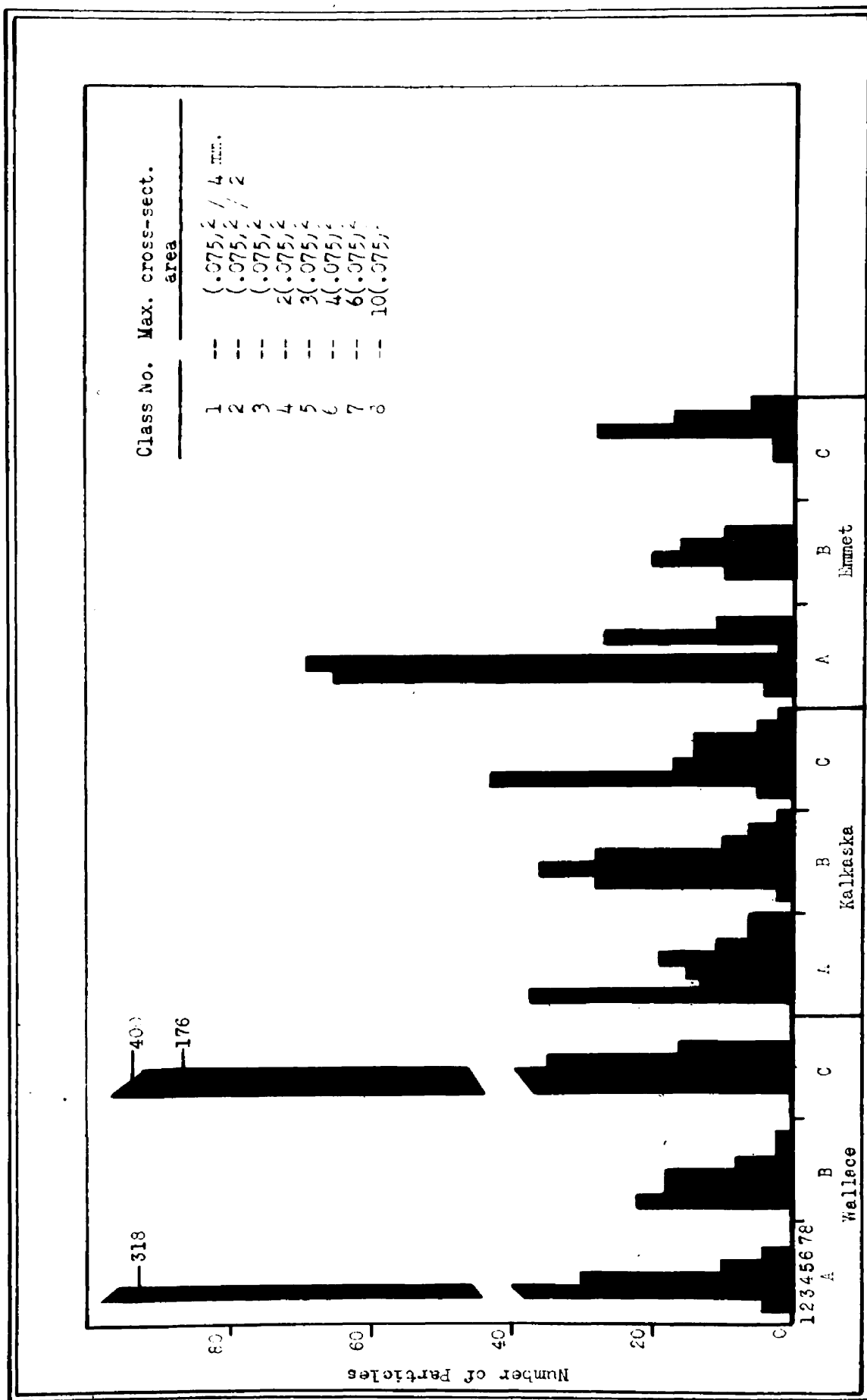


Figure 15. Microscopic count and grain size distribution of epidote in the fine sand fraction of the Group I soils. (20 grams of organic-free soil)

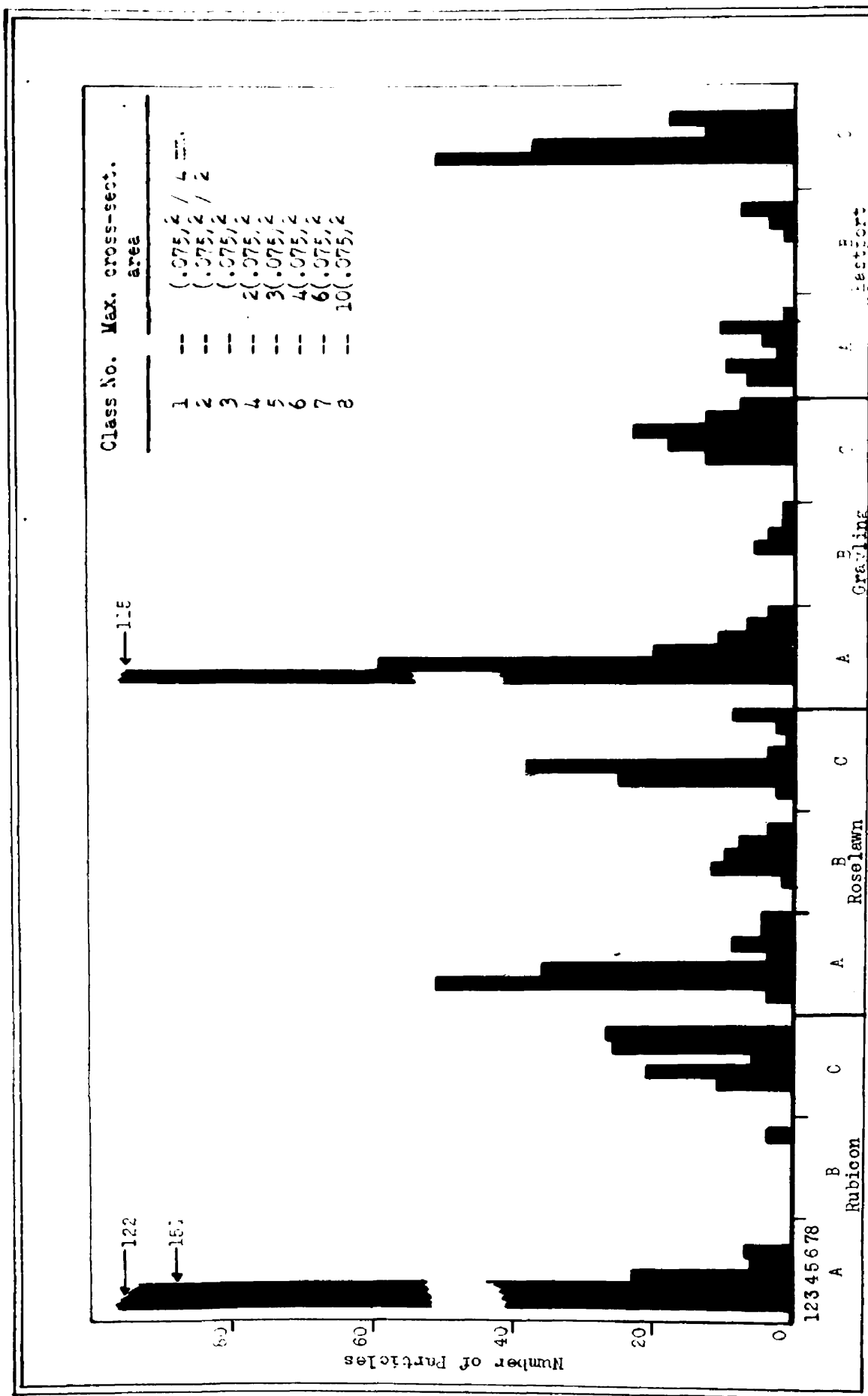


Figure 16. Microscopic count and grain size distribution of epidote in the fine sand fraction of the Group II soils. (20 grams of organic-free soil)

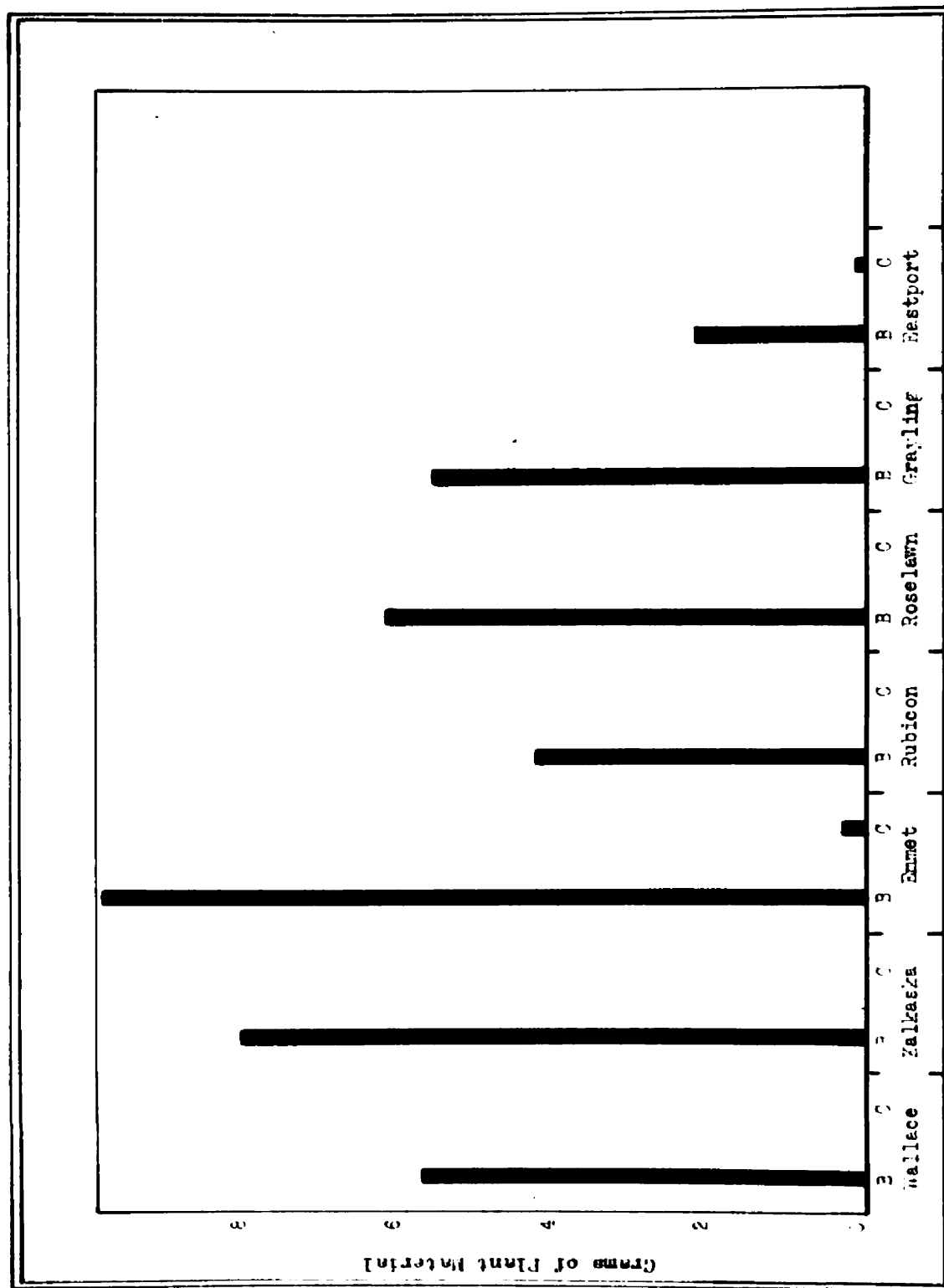


Figure 17. Neubauer tests. Increase of plant material over check.