DISTRIBUTION OF THE HEAVY MINERALS IN THE CLAYS OF MIDDLESEX COUNTY, NEW JERSEY

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SUMMARY

Elutriation of Cretaceous clay samples selected from the various stratigraphic horizons in Middlesex County, New Jersey, has afforded the material for the present petrographic research. Locations are shown on Plate 1. The main facts are the following:

1. The sandy residues from these clays have been studied in detail and the various grain sizes determined in their stratigraphic and areal distribution.
2. The various minerals, other than kaolin and quartz, have been identified.
3. The percentages of ilmenite, tourmaline, and zircon have been especially determined throughout the clay series and their relationships plotted stratigraphically and areally; this has made possible the correlation of clay beds whose exact relationships were hitherto unknown.
4. Total content of organic carbon has also been determined, and the relationships plotted in the same way as those of the heavy minerals.
5. The areal distribution of the various above-mentioned minerals and their relationships show that there is a distinct fan-like distribution of the clays; that the source of the material was from the northwest; and that it was carried by a definite river of very considerable size and drainage area.

INTRODUCTION

On the inner portion of the coastal plain of New Jersey, in the area within ten miles, more or less, of Perth Amboy, clays and sands have been extensively quarried for many years. The clays are used in the manufacture of fire-brick, hollow tile and stoneware; the sands, chiefly for building and road construction. They belong in age to the lower part of the Upper Cretaceous,[1] and include the following formations, beginning with the youngest in age:[2]

a. The Cliffwood clays, containing some glauconite, originally called the Clay-Marl series.

b. Laminated Sands, No. 4, showing thin clay layers and lenses.

c. The Amboy Stoneware clays, also very discontinuous; lenses in sand.

d. Sand Bed No. 3.

e. The South Amboy fire-clays, variable, lenticular and much replaced by and mingled with the sands above and below.

f. Sand No. 2, containing the so-called "Feldspar" and "Kaolin" Beds, which are lenticular bodies of white clay and partly disintegrated granitic gravel.

g. The Woodbridge clays, the most continuous formation of the series.

h. Fire Sand, No. 1, a formation which carries the artesian water of this vicinity.

i. The Raritan fire and terra-cotta clay, which consists of a series of discontinuous deposits in hollows in the bed-rock, and often grades into the latter.

It was thought that due to the extremely fine and complete water-sorting which the materials of these clays underwent during deposition, and the evidently undisturbed condition of most of them since that time, they should prove excellent subjects for quantitative microscopic study. This supposition has been largely supported by the results of the present research.[3] As the clays do not require crushing before they are submitted to the elutriation process, their grains appear unbroken when examined microscopically. This, it is obvious, has many advantages.

The clays of this Cretaceous series, of which about 40 samples from various horizons were studied, are highly plastic, and the finer grades of many of them contain practically no grit which may be felt when they are rubbed between the fingers. They are composed of kaolin, hydrated micaceous products, muscovite and similar material in grains of microscopic to submicroscopic size; and a proportion of fine-grained, angular sandy component which ranges in these samples from 12 to 69 per cent or more. The sandy material consists for the most part of sharp quartz grains (rounded grains are rare); in it are also found, as described in a former article published by the present writer,[4] the following minerals: magnetite, ilmenite, hematite, limonite, garnet, pyrite, zircon, rutile, tourmaline, etc., and pseudomorphs (evidently a kaolin mineral) after gypsum crystals. It seemed desirable to the writer to make quantitative determinations and measurements of these minerals, especially the ones which are most constantly present in the samples, in order to discover their relation to the story of the deposition of the clays. To this end, elutriation of the clays was undertaken, with the object of separating the granular portion from the lighter clay residue. All of the elutriation was done for the writer by the Department of Ceramics of Rutgers University, by Mr. John C. Gallup, under the direction of Professor George H. Brown. Each of the clay samples was washed through an apparatus composed of three small containers of graduated sizes, in which the rate of water flow was a known factor. Container No. 1, the largest, has a water velocity of 15 mm. per second, and the maximum size of grain of material retained in it is .04 mm. Container No. 2, with a water velocity of 0.7 mm. per second, retains grains of a maximum size of .025 mm., while No. 3 has a water velocity of 0.18 mm. per second and the maximum grain size retained is .01 mm. The size of grain will vary somewhat in practice, as it depends upon the specific gravities of the different minerals involved. The samples thus obtained were carefully weighed by Mr. Gallup, and delivered to the writer, who has tabulated the results. Later the samples were subjected to detailed microscopic study, during which many thousands of measurements and counts have been made. The conclusions reached are stated below.

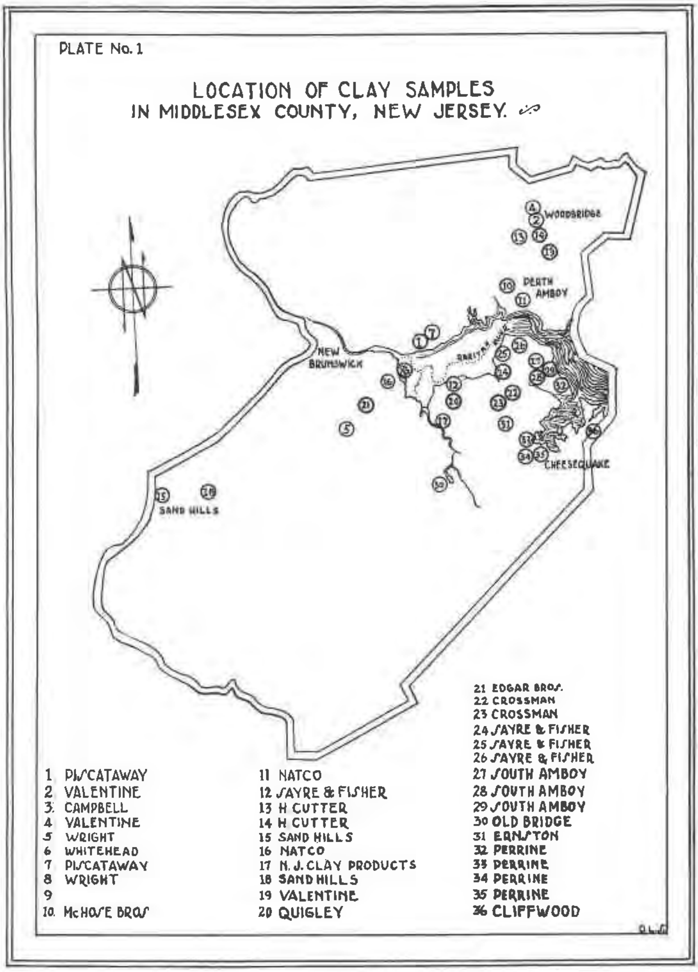

PLATE 1

Heavy Minerals in the Clays

There is, in each of the clays examined, a certain percentage of sandy material, which can be separated from the clay by elutriation. This material is largely composed of angular quartz grains. With the quartz there are also grains of the heavier and more unusual minerals, including such species as tourmaline, garnet and pyrite. Discarding the mineral pyrite, which is secondary, we find that there are a few characteristic minerals which are consistently present throughout the whole clay series. These minerals, of which there are three principal ones, have been quantitatively measured and the results plotted vertically and horizontally (areally) through out the clays. Consideration has also been given to the relations of these minerals to the kaolin mass of the clay itself. Chemical analyses to determine the distribution of the total organic carbon in the clays have also been made, and the results plotted.

Details of tests made and results obtained are given in Tables I and II.

Table I

Percentage of Sand Grains of Various Sizes Obtained from Elutriation of Clays

	Number and Location of Sample	Percentage by weight of residue				Percentages recast to 100%		
		Can 1	Can 2	Can 3	Total	Can 1	Can 2	Can 3
					%			%
Marine Beds. (Upper Cretaceous and Tertiary)	38. Upper Marl, Neptune, N. J.	28.20	26.22	14.10	68.52	41	38	21
	37. Middle Marl, Middletown, N. J.	40.05	25.02	18.10	83.17	48	30	22
	36. Cliffwood Clay (Oschwald) Keyport	27.65	2.54	27.20	57.39	47	6	47

TABLE I (*Continued*)

	Number and Location of Sample	Percentage by weight of residue				Percentages recast to 100%		
		Can 1	Can 2	Can 3	Total	Can 1	Can 2	Can 3
Amboy Stoneware Clays	35. Perrine Top Sand Clay, Cheesequake.	27.30	2.94	28.50	58.70	46	5	49
	34. Perrine Gray Clay Cheesequake.......	2.65	.71	27.28	30.64	9	2	89
	33. Perrine Red Mottled Cheesequake.......	2.15	7.20	12.30	21.65	11	33	56
	32. Perrine Gray Clay Morgan...........	.25	10.44	27.00	37.69	1	27	72
	31. Smith Gray Clay Ernston...........	2.10	7.80	27.20	37.20	6	21	73
	30. Raritan Sand Co. Gray Old Bridge....	4.54	12.92	28.55	46.00	10	28	62
	29. Old Prospect Pits, Red South Amboy..	12.17	1.62	31.17	44.96	27	4	69
	28. Old Prospect Pits, Yellow South Amboy	5.15	.76	15.75	21.66	24	3	73
	27. Old Prospect Pits, White South Amboy	1.43	5.43	24.47	31.33	4	17	78
South-Amboy Fire-Clays	26. Sayre & Fisher, Dark Gray, West of South Amboy...........	16.76	15.00	25.50	50.48	30	28	42
	25. Sayre & Fisher, Light Gray, West of South Amboy...........	7.50	4.00	5.97	17.47	43	23	34
	24. Sayre & Fisher, Light Gray, Burt Creek...	15.43	.51	3.26	19.20	81	2	17
	23. Crossman, Gray Clay Parlin............	.36	26.30	29.62	56.28	1	47	52
	22. Crossman Red Mottled Parlin.........	.18	.60	7.68	8.46	2	7	91
	21. Edgar Bros. Light Gray Milltown.....	4.04	2.31	18.59	24.94	17	9	74

TABLE I (*Continued*)

	Number and Location of Sample	Percentage by weight of residue				Percentages recast to 100%		
		Can 1	Can 2	Can 3	Total	Can 1	Can 2	Can 3
"Feldspar" Beds	20. Quigley White Clay Sayreville	.32	5.21	16.70	22.23	2	23	75
	19. Valentine (Feldspar) Woodbridge	.15	8.43	22:14	30.72	1	27	72
	18. Route 25 White Clay Sand Hills	.50	18.98	25.94	45.42	1	42	57
Woodbridge Fire-Clays	17. N. J. Clay Prod. Co. Gray, So. of Sayreville	7.65	20.09	41.15	68.89	11	29	60
	16. Natco, Gray West of So. River	1.47	6.58	39.15	47.20	3	14	83
	15. Lincoln Highway Gray, Sand Hills	2.50	1.25	8.35	12.10	21	10	69
	14. Hampton Cutter Gray Woodbridge	2.50	2.10	55.50	60.10	4	3	98
	13. Hampton Cutter Gray, Woodbridge	.55	4.20	39.25	44.00	2	9	89
	12. Sayre & Fisher Gray Sayreville	.23	9.27	43.31	52.81	1	17	82
	11. Natco Gray, Perth Amboy	4.12	10.88	44.60	59.60	7	17	76
	10. McHose Bros. Gray Keasby	4.36	10.55	41.60	56.51	7	19	74
Glacial (?) Clay	9. Gray Clay in Drift Elizabeth (glacial)	5.00	14.00	32.40	51.40	10	27	63

TABLE I (*Continued*)

	Number and Location of Sample	Percentage by weight of residue				Percentages recast to 100%		
		Can 1	Can 2	Can 3	Total	Can 1	Can 2	Can 3
Raritan Fire-Clays	8. Wright Dark Gray Milltown..........	.55	22.48	27.43	50.46	1	45	54
	7. Raritan Sand Co. Gray Piscataway...	.23	.83	11.44	12.50	2	6	92
	6. Whitehead Gray Island Farm, Raritan River............	2.26	6.85	28.32	37.43	6	18	76
	5. Wright Light Gray Milltown..........	.94	1.63	14.94	17.51	6	9	85
	4. Valentine No. Pit Gray Woodbridge...	6.73	.52	13.33	20.58	32	3	65
	3. Campbell Red Clay Route 25, Metuchen.	.27	1.41	20.96	22.64	1	6	93
	2. Valentine No. Pit Red Woodbridge....	2.33	7.20	35.02	44.55	5	16	79
	1. Raritan Sand Co. Red Piscataway....	.42	9.07	39.30	48.79	1	19	80

Thus a petrographic classification has been made, modified somewhat in stratigraphic order, to conform as far as possible with the known succession of the clay horizons as shown in the field. If the stratigraphic evidence shows that any part of this petrographic classification is incorrect, the latter arrangement should be modified to meet the proven conditions.

Some details of classification may prove of special interest, as follows:

Among the Raritan clays, No. 1 rests upon red shale and grades directly into it. No. 3, ten feet thick, also rests upon red shale. No. 2 is certainly no farther above red shale of the same sort. The gray Raritan clays Nos. 4 to 7 inclusive, lie just above the red clays. No. 8 is a dark gray clay lens in sand No. 1, ten feet above the gray clays just mentioned and is, in a sense, transitional between the Raritan and Woodbridge fire-clays.

No. 21, Edgar Brothers clay, at Milltown, is agreed by all field observers to belong in the Woodbridge fire-clay series. Petrographic classification would place it with the South Amboy fire-clays and hence it has been placed there in our chart, Plate 2. Practical experience in the use of this clay shows that its behavior is not like that of the rest of the Woodbridge clay series in general.

The gray lenticular clays in the sand pit of the Raritan Sand Company at Old Bridge, and the clays of similar appearance from the old Smith pits south of Ernston, appear to correlate with each other, both belonging to the Amboy stoneware clay series (see New Jersey Geological Survey, Clay Report 1904, page 170).

No. 35, the upper or top sandy clay of H. C. Perrine at Cheesequake, is a lenticular body in the white No. 4 sand, which overlies the Amboy stoneware clay proper; it is perhaps 50 feet below the base of the Cliffwood clay, No. 36, and is distinctly transitional between the stoneware clays and the latter clay.

The attempted correlation of the "feldspar" beds, Nos. 18, 19, and 20, brings to light some points of peculiar interest. The Valentine "Feldspar" deposit at Woodbridge is thus correlated on the basis of distribution of grain size, and also the relative proportions of tourmaline, ilmenite and zircon, with the Quigley white clay of Sayreville and the white clay lenses in sand which were lately exposed on the Sand Hills on Route 25, ten miles to the southwest. In the two relationships above mentioned these three clays differ radically from all the other clays examined and at the same time agree among themselves. The white clay of the Sand Hills is evidently a series of lenses in No. 2 sand. Whereas the clay of the old Knickerbocker pits (No. 15) along the old Lincoln Highway, two miles to the southwest of the white clay on Route 25, correlates with the Woodbridge fire-clay series, it appears that the trap rock of Rocky Hill, which is underneath the Sand Hills, was a monadnock of moderate height (100 feet or so), on the Fall Zone Peneplane, around whose base the Woodbridge fire-clay was deposited, and on whose top No. 2 sand with its white clay lenses was laid. The age of the Sand Hills deposits is thus established.

No. 26 is a clay which is about two feet thick where exposed, along Route 25, where the Lehigh Valley Railroad crosses it in Elizabeth, New Jersey, completely surrounded by reddish glacial drift of the Wisconsin epoch. The clay is seamed with limonite. It is very plastic, and in appearance and microscopic character closely resembles the Cretaceous clays herein described. Its appearance and petrographic analysis would make it seem closely similar to the Woodbridge fire-clay of the Cretaceous; but its position would appear to argue against its Cretaceous age, as it is 10 miles north of known Cretaceous exposures and has an elevation supposedly below the old Fall Zone Peneplane upon which the Cretaceous clays were deposited.

For comparison with the Cretaceous clays, a real glacial (Pleistocene) lake clay from the Hudson River at Catskill, New York, was elutriated. This shows percentages by weight as follows:

Can 1, 1.30%; can 2, 7.40%; can 3, 11.55%; Total material collected 20.25%.

This, reduced to a basis of 100%, gives 6%+37%+57% =100%. The material caught in the cans is flocculent and brownish, and the remainder which passes out with the wash water is a very fine-grained, evenly sized collection of sharp, angular ground rock dust. Thus its behavior is very different from that of the Cretaceous clays. This glacial clay shows very few heavy mineral grains, but does exhibit some of the characteristic small green tourmaline crystals which are present in all of the Cretaceous clays and are believed by the writer to have had their origin in the schists of New England.

Distribution of the Three Sizes of Grains of Sandy Residues Obtained by Elutriation (Table 1)

Vertical Distribution.

It is generally true that, throughout this entire series of clays, the finer material (kaolin, etc., and the smaller sand grains) greatly predominates in amount.

There was a steady increase, in general, in the amount of the *coarse* part of the sand (contents of can No. 1), as deposition progressed, from the Raritan clays at the bottom, through the Cliffwood clays to the Marls at the top, at the expense of the finer sandy material. Most of the variation in the residues is in the coarse material.

There is a general similarity in many of the samples taken from a general horizon, and in the Woodbridge clays the relations as to grain size are most nearly constant.

It does not seem possible to classify this sedimentary series by grain-size analysis, as the sediments themselves are too variable.

Areal Distribution of Total Sandy Residue.

Definite conclusions result from graphical plotting of areal distribution of the total sandy residue; in the Woodbridge clays there is a well-defined tendency of the fine-grained sandy material to increase in relative amount toward the east, that is, away from the mainland, at such a rate that within another 20 miles east of Sayreville, the formation would probably be largely sand. A well 724 feet deep at Barren Island, L. I., shows less than 100 feet of clay in the entire section; the rest is sand.

The coarse sand grains in these clays do not increase in relative numbers toward the east, but the relative number of the smaller sand grains does greatly increase. The relative number of the medium sized sand grains is small in proportion to that of the larger and smaller sand grains, and it does not vary much in areal distribution.

Quantitative Measurement of Heavy Mineral Content of the Clays

The following was the method used in estimating the percentages of the three most common heavy minerals present—tourmaline, ilmenite, and zircon—in the sandy residue obtained from the clays by elutriation:

The grains were immersed in oil under a cover-glass and spread out as evenly as possible, and all of the grains of heavy minerals counted in units of equal size by use of a micrometer ocular. Grains of tourmaline, ilmenite and zircon alone were counted in this test. For example, in the elutriated products from the Cliffwood clay of Oschwald from near Keyport, the following results were obtained on one series of tests:

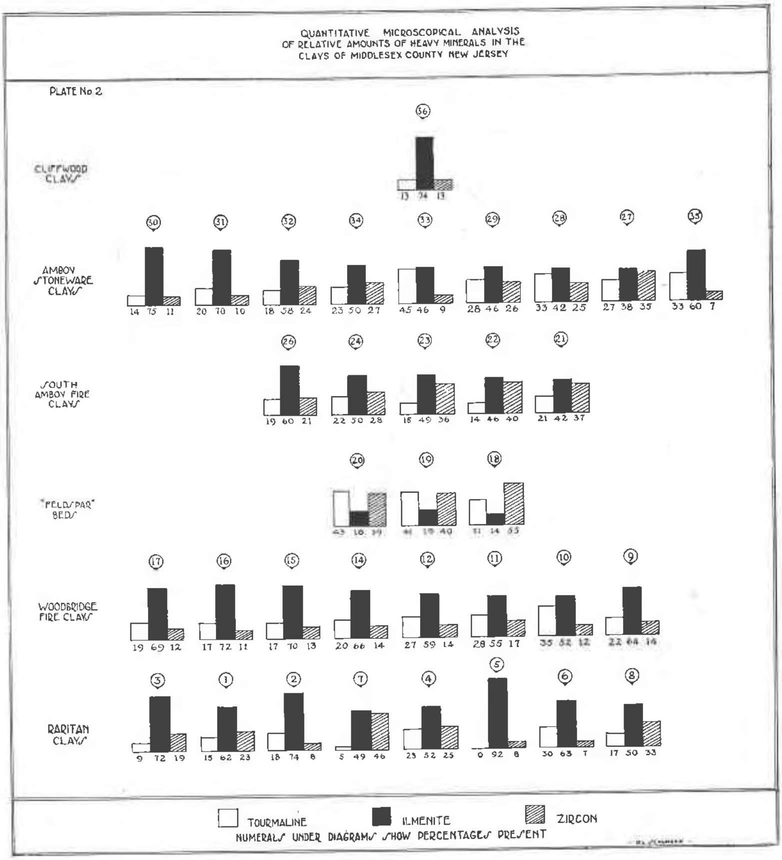

PLATE 2. Quantitative analysis of heavy minerals in clays of Middlesex Co., New Jersey.

In material from can 1, 7 units of tourmaline; 135 of ilmenite; and 12 of zircon.

This, reduced to a percentage basis, gives: tourmaline, 6%; ilmenite, 87%; zircon, 7%.

Similarly, in can 2, we find: 29% of tourmaline; 42% of ilmenite; and 9% of zircon.

In can 3 we discover, 3% of tourmaline; 88% of ilmenite; and 9% of zircon.

Then the average percentage of tourmaline in cans 1, 2, and 3, is $6+29+3\% \div 3 =$ about 13%. Similarly, the average percentage of ilmenite is 74%, and of zircon, 13%.

We thus arrive at the average percentage of these minerals in the clay, as represented in Plate 2.

Table II shows a summary of the findings in percentages of heavy minerals in the clays from various horizons.

Table II

Percentage of Heavy Minerals in Elutriation Residues from the Clays

	Number	36	35	34	33	32	31	30	29	28	27	26	24
		%	%	%	%	%	%	%	%	%	%	%	%
Tourmaline	Can 1	6	16	17	38	12	14	8	37	26	34	19	17
	Can 2	29	49	25	34	31	22	20	25	42	24	20	2
	Can 3	3	32	28	64	11	24	14	22	32	23	17	45
	Av.	13	33	23	45	18	20	14	23	33	27	19	22
Ilmenite	Can 1	87	63	53	54	48	74	89	44	48	33	53	33
	Can 2	48	49	50	49	41	64	55	40	26	24	55	74
	Can 3	88	64	41	33	84	73	82	54	52	58	72	43
	Av.	74	60	50	46	58	70	75	46	42	38	60	50
Zircon	Can 1	7	16	25	8	40	12	3	19	26	33	28	50
	Can 2	23	2	25	17	23	14	25	35	32	52	25	24
	Can 3	9	4	31	3	5	3	4	24	16	19	11	11
	Av.	13	7	27	9	24	10	11	26	25	35	21	23

	Number	23	22	21	20	19	18	17	16	15	14	12	11
Tourmaline	Can 1	16	11	6	40	0	18	23	6	12	22	32	18
	Can 2	10	8	25	44	61	26	24	30	25	14	28	20
	Can 3	21	24	33	45	63	50	8	16	13	23	20	43
	Av.	15	14	21	43	41	31	19	17	17	20	27	23
Ilmenite	Can 1	30	42	51	20	28	18	60	88	65	52	45	70
	Can 2	70	53	25	19	8	7	68	55	60	75	68	67
	Can 3	46	42	50	15	23	16	81	73	87	72	65	27
	Av.	49	46	42	18	19	14	69	72	70	66	59	55

TABLE II (*Continued*)

PERCENTAGE OF HEAVY MINERALS IN ELUTRIATION RESIDUE FROM THE CLAYS.

ZIRCON	Can 1	54	47	43	40	77	64	17	6	23	26	23	12
	Can 2	20	39	50	37	31	67	8	15	15	11	4	13
	Can 3	33	34	17	40	14	34	11	11	0	5	15	25
	Av.	36	40	37	39	40	55	12	11	13	14	14	17
	Number	10	9	8	7	6	5	4	3	2	1		
TOURMALINE	Can 1	27	10	3	14	15	0	15	9	19	14		
	Can 2	35	31	16	0	43	0	20	8	30	30		
	Can 3	44	24	32	0	33	0	35	10	5	1		
	Av.	35	22	17	5	30	0	23	9	18	15		
ILMENITE	Can 1	65	66	65	35	85	98	61	54	64	34		
	Can 2	50	55	44	55	52	90	52	71	63	54		
	Can 3	42	72	43	56	52	88	42	90	95	99		
	Av.	52	64	50	49	63	92	52	72	74	62		
ZIRCON	Can 1	8	24	32	48	0	2	24	37	17	52		
	Can 2	15	14	40	45	5	10	28	21	7	16		
	Can 3	14	4	25	44	15	12	23	0	0	0		
	Av.	12	14	33	46	7	8	25	19	8	23		

36. Cliffwood Clay (Oschwald) Keyport, N. J.
35. Perrine Top Sandy Clay Cheesequake.
34. Perrine Gray Clay Cheesequake.
33. Perrine Red Mottled Clay Cheesequake.
32. Perrine Gray Clay Morgan.
31. Smith Gray Clay Ernston.
30. Raritan Sand Co. Gray Old Bridge.
29. Old Prospect Pits Red South Amboy
28. Old Prospect Pits Yellow South Amboy
27. Old Prospect Pits White South Amboy
26. Sayre & Fisher, Dark Gray West of South Amboy.
24. Sayre & Fisher, Light Gray Burt Creek.
23. Crossman Gray Clay Parlin.
22. Crossman Red Mottled Clay Parlin.
21. Edgar Bros. Light Gray Milltown.
20. Quigley White Clay Sayreville.
19. Valentine (Feldspar) Woodbridge.
18. Route 25, White Clay Sand Hills.
17. N. J. Clay Products Co. Gray South of Sayreville.
16. Natco Gray Clay West of South River.

15. Lincoln Highway, Gray Clay
    Sand Hills.
14. Hampton Cutter Gray Clay
    Woodbridge.
12. Sayre & Fisher, Gray Clay
    Sayreville.
11. Natco Gray Clay
    Perth Amboy.
10. McHose Bros. Gray Clay
    Keasby.
9. Gray Clay in Glacial Drift
    Elizabeth.
8. Wright Dark Gray Clay
    Milltown.
7. Raritan Sand Co. Gray Clay
    Piscataway.
6. Whitehead Gray Clay
    Island Farm, Raritan River.
5. Wright Light Gray Clay
    Milltown.
4. Valentine North Pit Gray Clay
    Woodbridge.
3. Campbell Red Clay
    Route 25, Metuchen.
2. Valentine North Pit Red Clay
    Woodbridge.
1. Raritan Sand Co. Red Clay
    Piscataway.

In cases where data have not been fully given in this article, the cause lies in the writer's inability to obtain material to make the figures complete, on account of the extremely small amounts of some samples obtained from the elutriation of the original 20 grams of clay.

In taking clay samples from these formations, the same general horizon has been followed as far as possible, where direct comparison was desirable; but it is impossible to follow any given stratum very far, even from one clay pit to the next, or from one side of the Raritan River to the other, because practically all of them are more or less lenticular.

It is possible to obtain figures for average content of heavy minerals in a given clay, simply by immersing a smear of it in oil or water, on a microscopic slide under a cover-glass, and counting the various sandy grains, disregarding the clay body. Incident light is used to observe the secondary limonite grains, which then appear brown, and fresh pyrite, which looks brassy. As the clays generally contain more or less lignite, which in the field of the microscope is easily confused with iron ores, it is necessary to heat all such samples to redness for a few minutes before mounting them for microscopic examination.

In this connection it is apropos to point out that from this large collection of detailed data it should be possible to work out many features of the sedimentation process which has not been thought necessary to develop in this paper. Taking, for example, the case of the Woodbridge fire-clay sample from the Sayre & Fisher pits at Sayreville:

The average amount of the three heavy minerals, compared to the quartz, in the sandy residue elutriated from the clay appears as follows: Can 1, 6.3%; can 2, 5.8%; can 3, 1.7%. The total sandy residue obtained from the clay, including the heavy minerals, is (see Table I): Can 1, 1%; can 2, 17%; can 3, 82%. This means that 1%, the coarsest part of the sandy residue, contains 6.3% of the three heavy minerals; 17%, the medium sized sand, contains 5.8%; and 82%, which is the fine-grained part of it, contains 1.7% of the smallest heavy mineral grains.

But among the heavy mineral grains counted, tourmaline amounts to 27%; ilmenite 59%; and zircon 14%, of the total of these three heavy minerals.

Also, the total sandy residue in this case amounts to 52.81% by weight of the clay.

Relative Sizes of Heavy Mineral Grains

In elutriation of these clays in the laboratory, it is found, in many cases, that most of the heavy mineral grains settle into the first or largest can, No. 1, and are much scarcer in can No. 3. This shows that a very considerable proportion of the heavy mineral grains are large. This can be explained in the case of magnetite, ilmenite, and garnet by the fact that the smaller grains readily rust to limonite, and are swept away. Other mineral grains, like those of tourmaline, may have developed as crystals of fairly uniform size in a schistose rock.

Vertical Distribution of Heavy Mineral Grains

In the Raritan clays, at the bottom of the series, results show that:

In the red clays which rest upon Triassic shale and may have been derived from the latter by replacement, the residue is quartz, with grains and "worms" of kaolin, and the heavy minerals scarcely amount to 0.1%. In the gray Raritan horizons slightly above this, can 1 shows 2.4% of heavy minerals; can 2, 2.2%; and can 3, 1.5% (sample from Woodbridge, No. 4, from the north pit of M. D. Valentine & Company).

A normal clay of the Woodbridge clay series is slightly larger in heavy mineral content; compare Natco gray clay, from the pit on west side of Perth Amboy, with can 1, 4.5%; can 2, 3.0%; and can 3, 1.0%. There is a marked concentration of heavy mineral grains in the Woodbridge series, especially near Sayreville, where the gray clay of the Sayre & Fisher Company shows: can 1, 6.3%; can 2, 5.8%; can 3, 1.7%. There is also a similar concentration shown at the property of the New Jersey Clay Products Company. Such concentration is attributable to the presence of the buried ridge of the Palisade diabase, which here closely underlies the Woodbridge clay.

The South Amboy fire-clay is often extremely sandy and much of this sand is locally largely composed of the heavy minerals; as at the Sayre & Fisher pits near Burt Creek, where can 1 shows 15.52%; can 2, 3.74%, and can 3, 1.1%.

The Amboy stoneware clay shows a great decrease in the relative abundance of heavy minerals; as in H. C. Perrine's gray clay at Cheesequake: can 1, 2.8 %; can 2, 1.0%; can 3, 0.5%. In the marls there is a rarity of heavy mineral grains, to which reference has already been made.

Details for the various clay horizons are as follows (see Pl. 2):

	Tourmaline	*Ilmenite*	*Zircon*
Cliffwood Clay	13%	74%	13%=100%
Amboy Stoneware Clay (average of 9 localities)	26	53.7	20.3
South Amboy Fire-Clay (average of 6 localities)	17.7	52.1	30.2
"Feldspar" and "Kaolin" (average of 3 localities) (Granitic)	38.3	17	44.7
Woodbridge Fire-Clay (average of 8 localities)	22.6	64	13.4
Raritan Fire-Clay (average of 8 localities)	14.7	64.3	21

a. The sample of the Cliffwood clay which was chosen, shows a vast preponderance of ilmenite over tourmaline and zircon; and the latter two minerals are exactly balanced in amount.

b. The Amboy Stoneware Clays show a preponderance of ilmenite over tourmaline and zircon in every case, but there is no fixed relation as to relative amounts of tourmaline and zircon. Irregularity appears, as in the clays in the field.

c. The South Amboy Fire-Clays show preponderance of ilmenite, while the relative amount of zircon is always larger than that of tourmaline.

d. The "feldspar" and "kaolin" series of clay lenses in sand No. 2, show ilmenite in very subordinate amount; and in this respect they are different from any of the other clays.

e. The Woodbridge Fire-Clays show a preponderance of ilmenite over tourmaline and zircon in every case; and in every case the relative amount of tourmaline exceeds that of zircon.

f. The Raritan clays at the base of the Cretaceous, lenticular and irregular, show no characteristic similarity except the usual large amount of ilmenite.

The supply of tourmaline and of ilmenite is fairly constant throughout the Cretaceous clays, ilmenite being generally far more abundant than tourmaline.

The relative amount of zircon is small in the Raritan clays, which were largely derived from shaly bed-rock. The Woodbridge clays also show a relatively small amount. The "feldspar" and "kaolin" beds above this are partly composed of coarse granitic material, and hence show an increase in zircon and tourmaline. In the clays from thence upward the relative amounts of these latter minerals decrease, probably as the schists were covered up by the encroaching margin of the clays. In the still higher marls they are very scarce. The progressive increase of zircon and tourmaline from Raritan to Woodbridge clays may be the result of erosion into the rocks containing them, or more active drainage.

Ratio of Total Percentages of The Three Heavy Minerals (Ilmenite, Tourmaline, and Zircon) to the Total Quartz in the Elutriated Residue.

This ratio varies from 20% to about 1%, in the samples studied; most of the sandy residues show a ratio of from 1% to 5%, with the marls showing a much smaller proportion of heavy minerals (about one grain of 1000 of quartz, at most). Detailed work on the contents of the various cans has been prevented by lack of material, some of the elutriated residues having been very small to begin with. Contours based on areal distribution of this relationship give definite results (see Plate 3).

Magnetite and Unaltered Feldspar in the Clays

It appears that ilmenite (nonmagnetic) is much more plentiful than magnetite, and that most of the titanium in these clays is in ilmenite, which is plentiful, rather than in rutile, which is scarce. Magnetite is present to some small extent in the Raritan Clays, and in all of the rest except in the Woodbridge series, where a mere trace was found at one locality only. This indicates conditions of shifting sedimentation.

Unaltered feldspar was not found in the Woodbridge Fire-Clay samples, but it is present in about half of the other clays observed; particularly in the Cliffwood clay. The "feldspar" beds contain it at Valentine's pit in Woodbridge only. Other correlated clays are pure white kaolin for the most part. Some of the feldspar is plagioclase, and some without twinning may be orthoclase.

Determination of Total Organic Carbon Content of the Clays

The carbon in these clays exists mostly as disseminated material, which gives a dark color to many of them. At other times thin filaments of carbon are found filling leaf imprints, and again it forms logs of lignite, sometimes 40 feet long and a foot or more in diameter. Pyrite often partially or wholly replaces the lignite.

Determinations of carbon were made for the writer by Mr. Meredith F. Parker, who heated the samples and measured by absorption the amount of carbon dioxide driven off. The carbon content of the various clays is as follows:

36. Oschwald, Keyport	2.72%	17. N. J. Clay Prods.	1.09%
35. Perrine, top	1.77%	16. Natco, So. River	0.83%
34 Perrine, gray	0.14%	15. Knickerbocker	0.16%
33. Perrine, red mottled	0.10%	14. H. Cutter, Wbdge.	1.30%
32. Morgan	1.16%	12. S. & F., Sayreville	1.82%
31. Smith, Ernston	0.20%	11. Natco, Perth Amboy	1.34%
30. R. S. Co. Old Bridge	3.63%	10. McHose, Keasby	1.66%
29, 28, 27. So. Amboy	0.10%	9. Elizabeth	1.06%
26. S. & F., So. Amboy	1.27%	8. Wright, dk. gray	0.89%
24. S. & F., Burt Creek	1.56%	7. Piscataway, gray	0.13%
23. Crossman, Parlin	3.29%	6. Island Farm, gray	2.12%
22. Crossman, red mottled	0.15%	5. Wright, gray	0.23%
21. Edgar gray	1.86%	4. Valentine, gray	0.15%
20. Quigley, white	0.10%	3. Campbell, red	0.05%
19. Valentine "spar"	0.07%	2. Valentine, red	0.13%
18. Sand Hills, white	0.06%	1. Piscataway, red	0.09%

Areal Distribution of Heavy Minerals and of Carbon in the Clays

Plate 3 shows by means of contour lines, based upon percentages, that there is a regularity in the distribution of the heavy minerals and of total organic carbon content in the clays.

Fig. A shows that a relatively large amount of ilmenite, in small grains, was swept far out from the source of supply. In Fig. B we see that a relatively large amount of tourmaline was left near the mainland. Similar areal plotting of the zircon content also shows the same kind of distribution. The shapes of the ilmenite grains are angular and irregular. The tourmalines are perfectly formed prismatic crystals, which would roll for considerable distances very readily. Most of the zircon grains are not in the form of complete crystals, but in rounded or even spherical grains of small size;

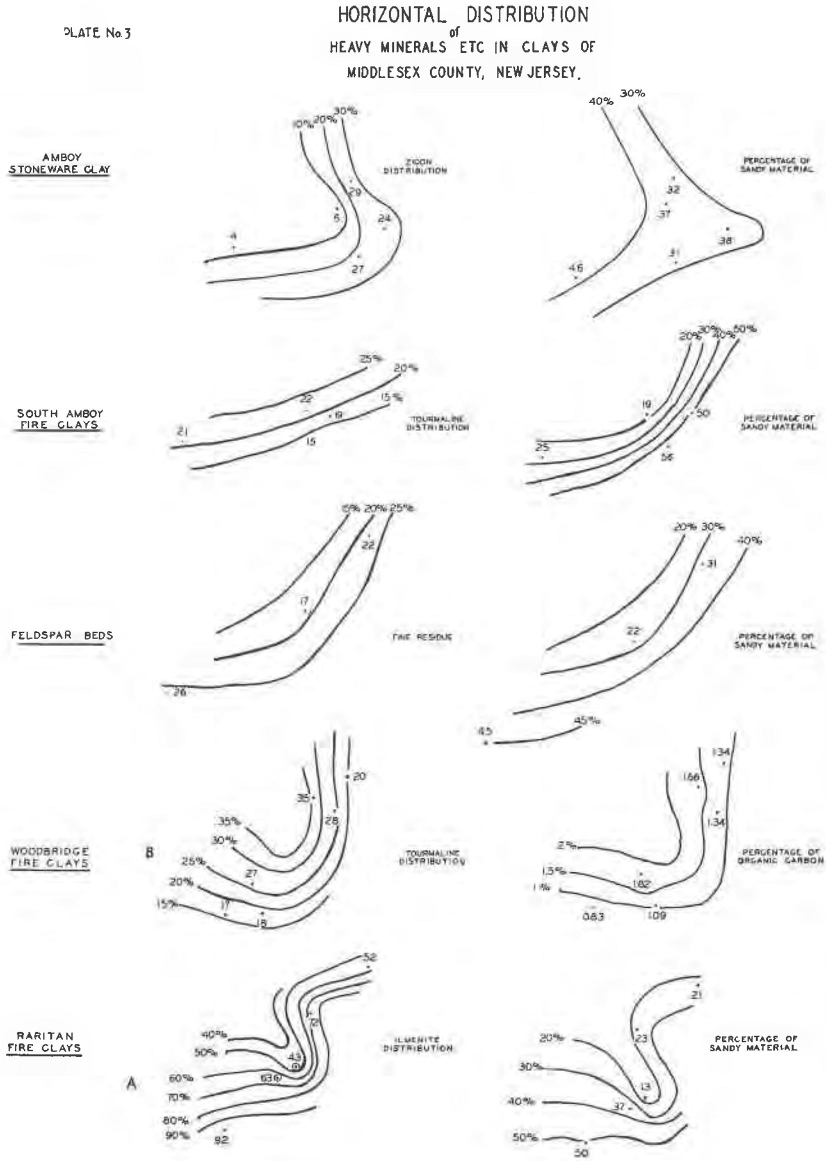
PLATE No. 3
HORIZONTAL DISTRIBUTION of HEAVY MINERALS ETC IN CLAYS OF MIDDLESEX COUNTY, NEW JERSEY.
AMBOY STONEWARE CLAY
ZIRCON DISTRIBUTION
PERCENTAGE OF SANDY MATERIAL
SOUTH AMBOY FIRE CLAYS
TOURMALINE DISTRIBUTION
PERCENTAGE OF SANDY MATERIAL
FELDSPAR BEDS
FINE RESIDUE
PERCENTAGE OF SANDY MATERIAL
WOODBRIDGE FIRE CLAYS
B
TOURMALINE DISTRIBUTION
PERCENTAGE OF ORGANIC CARBON
RARITAN FIRE CLAYS
A
ILMENITE DISTRIBUTION
PERCENTAGE OF SANDY MATERIAL

PLATE 3.

this shape is not due to attrition, but to the original poor development of the crystals which were formed, as seen today in the Manhattan schist and similar rocks.

The direction of water flow which distributed the material of these clays was plainly from the northwest, coming from the general direction of Plainfield, and spreading them outward fan-like, over the estuary of the present Raritan River. A survey of the percentages shown will disclose that extrapolation will carry them to a distance of perhaps 10 miles, to the northwest or southeast, where the various quantities will usually become 100% or 0%. Perhaps this is too uncertain to be seriously considered; but it has been found true in practically all cases, and may indicate that the vicinity of the Watchung ridges was the inner margin of deposition of this series of Cretaceous clays. This would in no way limit the much greater extent of the Marl series, deposited at later times. Perhaps the application of methods, similar to these, upon the marls might disclose the truth as to their former extent. This work the writer has begun but has not in any measure completed. It is difficult to work with the marls on account of the small number of grains of heavy minerals in them.

The clays exposed at Gay Head, Martha's Vineyard, Massachusetts, which are white, red, yellow, brown, and dark gray, show every indication of belonging to this same Upper Cretaceous series, and they have the same heavy minerals of the same typical appearance. They are very sandy; and considering their known distance above bed-rock, in the writer's opinion they may well be at the general horizon of the South Amboy fire-clays.

Special Investigation of the Mineral Content of the Clays

Considering the very refractory nature of the fire-clays, some little attention was paid to the presence of fluxing minerals, and the quantities of them which might be present.

Muscovite is visible under the microscope, in the fire-clay from Hampton Cutter's pit at Woodbridge to the extent of 6.3%, there being 93.7% of other minerals, in the elutriated residue in can No. 3. In the Sayre & Fisher pit at Sayreville the amount of muscovite in the corresponding can is 10.6%, and in the stoneware clay of H. C. Perrine, Cheesequake, 7.3%, for can No. 3. It is evident that there is a quantity of fine-grained mica which must have escaped with the clay body which was washed away; so these figures undoubtedly are low. At the same time, areal counts may overestimate the importance of the mica plates, which are thin and flat.

Many of these clays originally contained gypsum, which appears in tiny sheaf-like crystal aggregates; but all of it has changed by pseudomorphism to a kaolin mineral of composition precisely unknown, similar to beidellite or nontronite, and apparently intermediate between them.

Attempts to check the amounts of the oxides of boron, titanium, and zirconium were unsatisfactory. In the Valentine gray clay of the Raritan at Woodbridge, according to the heavy mineral content, $TiO_2 = 0.35\%$, $ZrO_2 = 0.215\%$, and $B_2O_3 = 0.00029\%$. On the corresponding gray Raritan clay at Piscataway, we find that $TiO_2 = 0.20\%$, $ZrO_2 = 0.24\%$, and $B_2O_3 = .004\%$. This is in general about half as much as the analyses from reputable chemical laboratories show; so it is apparent that about half of the material containing these compounds is so fine-grained that it has been washed away with the clay.

Acknowledgement is hereby made to Professor George H. Brown for his cooperation in the work which enabled this research problem to be investigated.

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