CONTRIBUTIONS FROM THE DEPARTMENT OF GEOLOGY
OF COLUMBIA UNIVERSITY
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BY

CHARLES REINHARD FETTKE, B. S., A. M.

Submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Faculty of Pure Science of Columbia University

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THE MANHATTAN SCHIST OF SOUTHEASTERN NEW YORK STATE AND ITS ASSOCIATED IGNEOUS ROCKS[1]

BY CHARLES REINHARD FETTKE

(*Presented by title before the Academy, 1 December, 1913*)

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[1] Manuscript received by the Editor, 1 December, 1913.

Introduction

The Manhattan schist is the uppermost or youngest of the three crystalline metamorphic formations which constitute the bedrock over the southeastern portion of New York State. The other two are the Inwood limestone and Fordham gneiss. These three formations are well exposed at numerous localities in New York, Westchester and the southern portions of Putnam Counties. The overlying mantle of Glacial drift, seldom very thick, has been removed over many portions of the area by erosion and in other places was never laid down. To the north, in Putnam and Dutchess Counties, the upper two formations, the Inwood limestone and the Manhattan schist, are not present, since a belt of gneisses constituting the Highlands of the Hudson intervenes. These gneisses are probably the equivalent of at least a portion of the Fordham gneiss of the region to the south. The overlying formations have here been removed by erosion. North of this belt a quartzite appears resting unconformably upon the gneiss. It is followed by a limestone and a slate.

The oldest of these formations exposed in southeastern New York State, the Fordham, is a black and gray banded gneiss made up largely of quartz, feldspar and biotite, with occasional grains of zircon and a very little apatite and titanite. Hornblende is occasionally abundant. Garnet is rare. The feldspar consists mostly of microcline and orthoclase, together with some albite-oligoclase. The rock shows a typical gneissoid structure, the alternate light and dark bands, which rarely exceed one or two inches in thickness, being due to the concentration of the mica along certain bands. A few thin beds of highly crystalline limestone are found associated with the gneiss. Dr. Charles P. Berkey[2] was the first to call attention to the fact that these are an integral part of the formation. The presence of interbedded limestone indicates the sedimentary origin of at least a portion of this formation. Dr. Berkey has shown that a further subdivision of these basal gneisses is impracticable. He correlates them with the Grenville series of the Adirondacks and Canada, which are known to be of pre-Cambrian age. Associated with them are a large number of igneous intrusive masses whose composition varies from that of granite to that of diorite. Most of these intrusives have also been subjected to metamorphic agencies so that they now appear as gneisses.

A quartzite occasionally appears in the upper portions of the Fordham gneiss to which the name Lowerre has been given, since it is from that

[2] "Structural and stratigraphic features of the basal gneisses of the Highlands." N. Y. State Mus. Bull. 107, pp. 361-371. 1907.

locality just north of the New York City limits that it was first described. This quartzite can be studied well at Sparta, a mile south of Ossining along the New York Central Railroad tracks, and also just east of Hastings-on-Hudson. It seldom exceeds one hundred feet in thickness and apparently grades into the underlying gneiss. None of the outcrops can be followed for any considerable distance laterally and they are not of common occurrence.

The Inwood limestone follows the Fordham gneiss, but in some localities a thin bed of quartzite intervenes, as is mentioned above. Typically, this limestone is rather coarse-grained and crystalline, reaching a maximum thickness of about eight hundred feet. Locally, where the original limestone was impure, tremolite and diopside occur in it and certain beds are quite micaceous, containing large amounts of phlogopite. Much of it runs high in magnesia and grades into a dolomite, but comparatively pure limestone beds are also present.

The exact nature of the contact of this limestone with the underlying gneiss affords a problem which is difficult to solve. Apparently, the bedding planes of the limestone are parallel to the banded structure of the gneiss, and, if this banded structure represents the stratification planes of former sediments from which the gneiss was derived, it would appear that no marked unconformity exists between the two. This relationship has been particularly well brought out by the contacts in the tunnels of the Catskill aqueduct across the formations. In the tunnel underneath the Harlem River just below High Bridge, no deviation from parallelism in the banding of the gneiss and the bedding of the overlying limestone at the contact, which is a sharp one, could be detected. No quartzite is present here, but a thin seam of pegmatite occurs along the contact. It seems that a slight amount of faulting movement has taken place along the contact, which would naturally be a weak zone, but no brecciation could be detected. A short distance beyond this contact, a bed of light gray gneiss several feet thick was encountered in the limestone. Its foliation is also parallel to the bedding of the limestone.

Under the microscope (Pl. XII, Fig. 1), this gneiss is seen to be made up largely of feldspar, quartz and mica. The feldspar is largely microcline, with some orthoclase and plagioclase present. Biotite is the most prominent mica present, only a little muscovite appearing now and then. The biotite is a deep brown variety showing intense pleochroism from light yellow to deep brown. Occasional minute rounded grains of zircon and isolated calcite crystals were noticed. The mica shows more or less parallel orientation, thus giving the rock its gneissoid structure, while the feldspar and quartz occur in interlocking grains of medium texture and uniform size.

The contacts of this gneiss with the limestone are quite sharp, but nevertheless it can only be interpreted as a recrystallized interbedded clastic sediment apparently of about the composition of an arkose.

The underlying Fordham gneiss has a light gray color and a distinctly gneissoid structure, being made up of a series of alternating light and dark bands. On the hill just east of the Harlem River in this vicinity, it is very intricately folded and contorted. Under the microscope (Pl. XII, Fig. 2), it is seen to be made up largely of feldspar, quartz and mica. The feldspar is mostly microcline, although some orthoclase and plagioclase are also present. The mica is for the most part a deep brown biotite with some muscovite. A little sericite occurs as an alteration product derived from the feldspar. Cataclastic structure is well developed. The feldspar and quartz grains are, therefore, not uniform in size and are usually elongated parallel to the foliation.

The difference in structure between this gneiss and the interbedded one is probably due to the fact that the limestone on either side of the interbedded gneiss protected it from the intense crushing effect of the forces accompanying the dynamic metamorphism which developed the cataclastic structure in the underlying gneiss and, therefore, only simple recrystallization occurred.

The same relation between the underlying gneiss and the limestone was shown in a similar tunnel through these formations near the lower end of Manhattan Island and also in the excavations for the dam at Kensico.[3]

The Inwood limestone is succeeded by the Manhattan schist. This consists essentially of a coarse, quartz-mica-feldspar schist which represents a recrystallized sedimentary rock of more or less argillaceous composition. As would be expected in such a formation, there is considerable variation from place to place and even in the same outcrop. At the contact, the limestone frequently grades into the schist. The beds of schist are also interbedded with the limestone and *vice versa.* Associated with the mica schist are certain other types of rock, some of which are schists, others gneisses, while still others are massive. They are undoubtedly of igneous origin. In composition, they range from very siliceous to very basic types. Their relation to the schist is such that it appears quite evident that they were intruded into it in part previous to, in part during, and in part after the period of metamorphism. It is to a description of the Manhattan schist and its associated igneous rocks that this paper is mainly devoted.

All of these formations have undergone intense metamorphism and have been folded into a series of steep anticlines and synclines, which are

[3] Oral communication by Dr. Charles P. Berkey.

usually unsymmetrical and frequently are overturned toward the west. The axes of the folds have a general northeast and southwest trend and usually have a gentle pitch toward the southwest. As a result of later planation through erosion, the formations are now exposed in a series of fairly parallel belts running nearly northeast and southwest. The limestone belts on account of their easier erosion are usually carved out by the valleys. Of the other two formations, the Fordham gneiss is the most resistant one, but usually the outcrops of both these formations are marked by ridges. Faulting in two directions, parallel with the folds and across them, has occurred. This has complicated their exposures. The limestone which normally should appear between the schist and gneiss has at times been cut out entirely or else its apparent thickness has been considerably reduced.

Historical Review

Since the region underlain by the Manhattan schist was explored and settled long before the science of geology had begun to attract any attention in this country, we find references made to the local formations as soon as men began the study of geology in North America.

One of the earliest references to the Manhattan Schist appeared in P. Cleveland's "Elementary Treatise on Mineralogy and Geology," which was published in 1816. In it H. H. Hayden called attention to a granite ridge which crossed Manhattan Island, appeared again at Hurlgate on Long Island and then extended into Connecticut. This ridge is now known to have been merely a protruding portion of the Manhattan schist which underlies the greater part of the island. William Maclure's first geological map of the United States appeared in the same volume. He placed the rocks underlying Manhattan Island in his primitive formation.

Among other of the earlier discussions on the geology of southeastern New York is that of Samuel Akerly,[4] who described the formations underlying Manhattan Island and Westchester County in 1820. Akerly recognized granites, gneisses, schists and limestones, all of which he placed in the Primitive formation on account of their crystalline character and absence of fossils.

L. D. Gale[5] in 1839, in his account of the geology of New York County, described the rocks as consisting chiefly of gneisses and associated serpentine, hornblende, primary limestones and anthophyllite rock.

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[4] An essay on the geology of the Hudson River, and the adjacent regions, illustrated by a geological section of the county, from the neighborhood of Sandy Hook, in New Jersey, northward, through the Highlands in New York, towards the Catskill Mountains. New York, 1820.

[5] "Report on the Geology of New York County." Third ann. rept. Geol. Surv. New York, pp. 177-199. 1839.

W. W. Mather, who was working on the geology of the first district comprising the southeastern portion of the State, also began the study of these formations. He published his first article in 1838,[6] and in his final report in 1843[7] on the geology of the first geological district for the New York survey gave the first comprehensive discussion of the geology and relationship of the Poughquag-Wappinger-Hudson River series and the Inwood limestone and Manhattan schist to the south. He traced the gray semi-crystalline limestone and overlapping slate north of the Highlands through their various stages of metamorphism into the white and gray crystalline limestones and mica schist to the east. The more crystalline Inwood limestone and overlying Manhattan mica schist with associated hornblende schist and granite intrusions to the south of the Highlands, he considered the equivalent of the above series, but in a more highly metamorphosed phase.

Another paper published about this time, dealing with the geology of a portion of this region, is one by Issachar Cozzens[8] on the geological history of Manhattan Island. He divides the formations of the island into the following series: Granite, syenite, serpentine, gneiss, hornblende slate, quartz rock occurring as veins, primitive limestone and diluvium. A map accompanying the report shows the distribution of these different formations. The relationship of the formations to one another is indicated by a number of cross-sections. Cozzens conceived the island to be underlain by a huge batholith of granite from which the granite dikes radiated out.

In 1867, R. P. Stevens,[9] in his paper on the geology of New York Island, proposed the name "Manhattan Group" for the formations underlying the island which he believed to be the equivalent of Emmons's old Taconic system, now known to represent Cambrian and Ordovician strata that have been highly metamorphosed. Stevens considered the granite dikes which are so numerous on the island to be of metamorphic origin, the same as the gneiss itself. The same applies to the hornblende, anthophyllite and other masses of rock frequently found. He thought that they represented simply different conditions of the same elementary material as the gneiss, which had merely undergone different forms of metamorphism.

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[6] "Report of the geologist of the first geological district of the State of New York." Second ann. rept. Geol. Surv. New York, pp. 121-183. 1838.

[7] Geology of New York, Part I, comprising the geology of the first geological district. Albany, 1843.

[8] A geological history of Manhattan or New York Island, together with a map of the island and a suite of sections, tables, and columns for the study of geology. New York, 1843.

[9] "Report upon the Past and Present History of the Geology of New York Island." Annals N. Y. Lyc. Nat. Hist., Vol. VII, pp. 108-120. 1867.

In 1878, Professor J. S. Newberry[10] stated that it was his opinion that the formations underlying Manhattan Island were Laurentian in age, although he was not in a position to make a positive assertion to that effect. The fact that a mottled serpentine[11] occurs on Manhattan Island which very closely resembles the Moriah marble of the Adirondacks which is known to be of Laurentian age he regarded as very strong evidence of the pre-Cambrian age of the former.

The most important contribution, however, to our knowledge of the formations of southeastern New York State after Mather had published his final report on the first geological district was the result of the work done by Professor James D. Dana in this region during the 70's. In 1880 he published a paper[12] on the geological relations of the limestone belts of Manhattan County. After a careful and detailed study of the limestone belts both to the north and to the south of the Highlands, he came to the conclusion that they were of the same age. He states that the limestones and adjoining schists of Westchester County are younger than the Highland Archean and are probably Ordovician and in part Cambrian in age. He considers that Westchester County was topographically the southern part of the Green Mountain elevation, the axis passing along the Connecticut-New York boundary line and extending through Manhattan Island. He also pointed out that the grade of metamorphism followed the same rule south as north of the Highlands, being of greatest intensity to the south and eastward, since the limestones and associated phyllites northwest of Peekskill were the least metamorphosed of those occurring south of the Highlands, while those of the central and eastern portions of the county and in the western part also were usually very coarsely crystalline. The limestones at Verplanck and Crugers on the other hand have only a moderately crystalline texture. They occupy an intermediate position between the least crystalline and the more coarsely crystalline areas.

James Hall in his report on the building stones of New York State[13] in 1886 followed Dana and correlated the marbles quarried in Westchester County and those of Dutchess County, western Connecticut and Massachusetts and Vermont. He placed them in the Quebec group.

Professor James F. Kemp in a paper on the geology of Manhattan

[10] "The geological history of New York Islands and Harbor." Pop. Sci. Mthly., Vol. 13, pp. 641-660. 1878.

[11] Trans. N. Y. Acad. Sci., Vol. I, pp. 57-58. 1881-82.

[12] "On the geological relations of the limestone belts of Westchester County, New York." Amer. Jour. Sci., 3rd ser., Vol. 20, 1880, pp. 21-32, 194-220, 359-375, 450-456; Vol. 21, 1881, pp. 425-443; Vol. 22, 1881, pp. 103-119, 313-315, 327-335.

[13] "Report on building stones." 39th ann. rept. N. Y. State Mus. Nat. Hist., pp. 186-225. 1886.

Island[14] in 1887 described the formations underlying the island, with a discussion of their mineralogical composition, origin and structural relationships.

During the late 80's, Dr. F. J. H. Merrill did much field work for the New York State Survey and the United States Geological Survey in the southeastern part of the State both in the Highlands themselves and in the metamorphic area to the south. In his first paper[15] in 1890 on these formations, he describes, under the term "Manhattan Group," the Manhattan schist, Inwood limestone, and Fordham gneiss, and states that he is in doubt as to whether to place this group in the pre-Cambrian or to correlate it with the slates, limestones and quartzites of Ordovician and Cambrian age north of the Highlands. The fact that there is a marked unconformity between the lower Cambrian quartzite and the pre-Cambrian gneiss north of the Highlands and that no such unconformity has yet been found between the Manhattan Group and the underlying beds south of the Highlands would seem strong evidence against such a correlation. On the other hand, he points out that no unconformity has yet been found between the partly metamorphosed strata of Peekskill Hollow, Tompkins Cove and Verplanck's Point, which he considers to be of Ordovician age, and the metamorphic beds of the Manhattan group which adjoin them, although such an unconformity would be expected if the latter are of pre-Cambrian age. In a later report[16] he makes the statement that the two series are equivalent, basing his conclusion on the relation of the quartzite, limestone and schist of Westchester County to the underlying gneiss, as this relation is precisely similar to that of the Paleozoic strata in southern Dutchess County and Putnam County to the subjacent gneiss, and from the nearly complete stratigraphic continuity. This statement apparently is contradictory to the one made in the previous paper quoted, where attention was called to the fact that there was a marked unconformity north of the Highlands, while none such had been found to the south. The Fordham gneiss of the Manhattan group, as previously defined, is considered to be pre-Cambrian in age, possibly Algonkian. The break between it and the Paleozoic is thought to be marked by a stratum of thinly bedded quartzite which crops out occasionally and is followed by the Inwood Limestone.

[14] "The geology of Manhattan Island." Trans. N. Y. Acad. Sci., Vol. VII, pp. 49-64. 1887.

[15] "On the metamorphic strata of southeastern New York." Am. Jour. Sci., 3rd ser., Vol. XXXIX, pp. 383-392. 1890.

[16] F. J. H. MERRILL: "The geology of the crystalline rocks of southeastern New York." 50th ann. rept. N. Y. State Mus., Vol. I, pp. 21-31. 1896.

Merrill's correlation was quite generally accepted as the correct one until 1907, when Dr. Charles P. Berkey[17] published a paper on the basal gneisses of the Highlands, based upon field work done by him in the Tarrytown and West Point quadrangles. He does not accept the correlation of Merrill and others and presents very strong evidence that the Inwood-Manhattan series south of the Highlands and the Poughquag-Wappinger-Hudson River series, to the north, are not equivalent. According to his position there are then the following six formations in relative order from the top downward overlying the basal gneisses:

(6) Hudson River phyllite or slate, which is very thick.
(5) Wappinger fine-grained blue and white banded limestone, about one thousand feet thick.
(4) Poughquag fine-grained quartzite, three hundred to six hundred feet thick.
(3) Manhattan coarsely crystalline mica schist, which is very thick.
(2) Inwood coarsely crystalline limestone, two hundred to eight hundred feet thick.
(1) Lowerre thin schistose quartzite, zero to one hundred feet thick.

The Lowerre quartzite south of the Highlands is closely related to the underlying gneiss, whenever it appears, which is not very frequently. It is thin when it does occur, rarely exceeding one hundred feet in thickness, and is always conformable with the associated gneiss. The Poughquag quartzite north of the Highlands on the other hand is usually much thicker, three hundred to six hundred feet, and rests with a marked unconformity upon the underlying gneiss. The relationship of these formations in the region northeast of Peekskill in the Peekskill Creek and Sprout Brook Valleys led Dr. Berkey to conclude that the two series could not be regarded as the same in age. The quartzite-limestone-phyllite series of the Peekskill Valley section he considers to belong to the Poughquag-Wappinger-Hudson River group, representing a down-faulted block of these once overlying formations into the older strata. A mile to the northwest across a ridge another belt of limestone occurs in the Sprout Brook Valley. This limestone is coarsely crystalline in contrast with the finely crystalline limestone of the Peekskill Creek section and contains silicate minerals and pegmatite intrusions which are absent in the latter. No quartzite whatever occurs in either margin of it, while the Peekskill Creek limestone has five hundred feet of quartzite conformably beneath it. The limestones of these two valleys can hardly be considered the same, and, if the Sprout Brook limestone is the equivalent of the Inwood, as Dr. Berkey thinks, the less metamorphosed Peekskill Creek limestone is

[17] "Structure and stratigraphic features of the basal gneisses of the Highlands." N. Y. State Mus. Bull. 107, pp. 361-378. 1907.

clearly shown to be of later age and the Inwood limestone-Manhattan schist series cannot be the equivalent of the Wappinger limestone-Hudson River slate series, represented here, but must be of earlier age and hence pre-Cambrian.

There are, therefore, at present two contrasting views: first, that the Inwood limestone and Manhattan schist series is of Cambro-Ordovician age, as held by Merrill, Dana, Mather and others; and second that it is of pre-Cambrian age, as held by Dr. Berkey. The present writer has made a rather detailed study of the Manhattan schist and its associated rocks as developed in the southeastern portion of the State of New York south of Highlands and has compared it with the Hudson River slates, phyllites and schists north of the Highlands to see what light such a study might throw on the problem from a petrographic standpoint. Typical localities were studied in detail and most of the areas of schist exposed were visited. A detailed structural study, however, involving very careful geologic mapping of large portions of the area underlain by these formations was not attempted.

Manhattan Schist

Areal Distribution

The Manhattan schist is exposed in a series of fairly broad, roughly parallel belts having a general northeast-southwest trend in the region south of the Highlands of the Hudson and east of the Hudson River (see map, Pl. XV). West of the Hudson River the Newark formation of Jura-Triassic age has concealed them with the exception of a small area in the vicinity of Tompkins Cove just south of the Highlands. The belted nature of the outcrops of this and the underlying formations, as has already been explained, is due to the erosion of a series of anticlines and synclines whose axes have a northeast-southwest trend. The schist occurs as far north as the southern portion of Putnam County in this area. Farther north the rest of Putnam and the southern portion of Dutchess County are underlain by the older gneisses of the Highlands, the younger formations having been entirely removed by erosion. The use of the term "Manhattan" has been confined entirely to those schists which make up the uppermost or youngest of the bedrock formations occurring in southeastern New York State in New York, Westchester and Putnam Counties. In Connecticut the continuation of the schists has been described under the name of "Berkshire," as given to them by the Connecticut Geological Survey.[18]

[18] Conn. Geol. and Nat. Hist. Surv. Bull. No. 6, pp. 91-92. 1906.

PETROLOGY

The Manhattan schist as typically developed on Manhattan Island consists chiefly of a dark coarsely crystalline mica schist. In a hand specimen biotite, muscovite, quartz, feldspar and some garnet can usually be recognized. The relative amounts of these different minerals in a particular specimen will vary greatly from place to place. In some cases, the micas greatly predominate over the other constituents, and the rock often shows a crenulated structure where it has undergone intense folding and crumbling. Often considerable amounts of feldspar are present, but in other cases, this constituent is almost entirely absent. Garnet is also more abundant in one place than another. In occasional seams, the rock is made up largely of quartz and feldspar with only a little mica in small flakes. The rock takes on a gray color and is less coarsely crystalline, the structure becoming gneissoid rather than schistose. Some of these grade almost into a quartzite, as the amount of feldspar present grows less. On Manhattan Island, however, the micaceous varieties are greatly in excess over the others.

A thin section made from a typical specimen of the micaceous variety taken from the site of the Journalism Building of Columbia University, at the southeast corner of West 116th Street and Broadway, shows under the microscope a coarsely crystalline texture and marked foliated structure (Pl. XIII, Fig. 1). The chief minerals present are biotite, muscovite, feldspar, garnet and a little quartz. Magnetite is fairly abundant and small amounts of pyrite are also present. Several grains of staurolite have been noticed. The biotite is a dark greenish-brown, intensely pleochroic variety. It is practically always oriented with its basal plane in the plane of schistosity, to which cause the foliation of the schist is principally due. Muscovite is not nearly as prominent as the biotite. It is often intergrown with it and shows a similar orientation in the plane of foliation. The space between the micas is occupied by the feldspar and quartz. The outlines of these minerals are quite irregular and they are closely interlocked. They are usually quite free from inclusions. Plagioclase is the most abundant feldspar present, although some orthoclase also occurs. The plagioclase is optically positive and belongs to the andesine variety. It has a maximum extinction angle of 20° in sections cut perpendicular to the albite lamellæ. The garnet is a light pink variety occurring usually in idiomorphic crystals which reach a diameter of 1.4 millimeters. Analysis 1 quoted in a later paragraph gives the chemical composition of this specimen.

A thin section of the light gray gneissic variety from Shaft 18 of the Catskill Aqueduct at West 42nd Street near Fifth Avenue, where it occurs in a belt about two feet wide interbedded with the typical micaceous type, on the other hand shows a medium-grained crystalline texture and only slightly foliated structure (Pl. XIII, Fig. 2). The principal constituent minerals are quartz, feldspar and biotite. Apatite is present in appreciable amounts in minute lath-shaped crystals. The feldspar consists of both orthoclase and plagioclase. The latter has a maximum extinction angle of 22° in sections at right angles to the albite lamellæ and is optically positive. It is evidently andesine. Both the quartz and the feldspar occur in allotriomorphic, interlocking grains. The biotite is a dark greenish brown, intensely pleochroic variety. The chemical composition of this type of schist is given under analysis 2 on page 212.

Closely related to the gray gneissoid variety just described is a type occasionally found in which the amount of feldspar is very small, the predominant mineral being quartz, so that the rock practically becomes a quartzite. A section of a specimen from West 155th Street and Tenth Avenue shows a medium-grained crystalline texture and slightly foliated structure. The rock is made up largely of quartz with some feldspar and biotite. Magnetite and a little apatite are also present. The biotite occurs in small, usually irregular flakes whose basal sections are oriented parallel to the plane of foliation. It shows marked pleochroism from light greenish yellow to deep greenish brown. The quartz and feldspar occur in allotriomorphic, closely interlocking grains. The feldspar consists of both orthoclase and plagioclase. The latter shows extinction angles up to 8° in sections at right angles to the albite lamellæ and is probably oligoclase.

Another variety which has a comparatively fine crystalline texture and shows only moderate foliation has the biotite occurring in numerous small flakes showing parallel orientation in a matrix of quartz and feldspar. The rock has a dark color. A specimen collected two and one-half miles north of New Rochelle along the Westchester Railroad when examined in thin section under the microscope shows the rock to consist mostly of quartz, biotite and feldspar and minor amounts of pyrite, magnetite and apatite. The biotite is a dark reddish brown variety showing intense pleochroism from light yellowish brown to deep reddish brown. The quartz and feldspar occur in allotriomorphic, interlocking grains. Both orthoclase and plagioclase feldspar are present, the latter giving extinction angles running as high as 39° in sections at right angles to the albite lamellæ. This would indicate labradorite.

The schist in the vicinity of New Rochelle and northeast of that point becomes for the most part very feldspathic in composition and takes on a gneissoid structure. A thin section from a specimen collected east of Pelhamville shows a medium-grained crystalline texture and foliated structure. The principal minerals are feldspar and quartz in allotriomorphic, interlocking grains, together with smaller amounts of biotite and muscovite. A little apatite is present as needle-like inclusions in the feldspar and quartz. An occasional grain of zoisite, a little magnetite and a few rounded grains of zircon also occur. The feldspar which is the most abundant mineral present consists of both orthoclase and plagioclase. The plagioclase is an andesine variety, being optically positive and showing extinction angles up to 10° in sections at right angles to the albite lamellæ. The biotite occurs in small flakes whose basal sections are in the plane of foliation. It shows marked pleochroism from light brownish yellow to deep brown.

Farther northeast, in the vicinity of Rye, most of the Manhattan schist formation becomes very quartzose in composition. Alternating with the thicker beds of quartzitic schist are thinner seams which are more micaceous and hence show foliation to a much more marked degree. The quartzitic schist has a light gray color and a medium-grained texture. Examination under the microscope shows that it is made up largely of irregular interlocking grains of quartz and minor amounts of feldspar, mostly plagioclase of an oligoclase-albite variety, giving extinction angles up to 8° in sections at right angles to the albite lamellæ and being optically positive. Some biotite of a deep greenish brown variety and a little muscovite are also present. A few minute rounded grains of zircon may be seen.

A gneissoid to schistose quartz-mica-feldspar rock probably belonging to the Manhattan schist formation occurs in the east central portion of Westchester County. It has been considered a part of this formation by F. J. H. Merrill[19] in mapping the lower Hudson sheet for the New York State Survey and also by Edson S. Bastin,[20] who examined the pegmatites occurring in it at Bedford Village. Lea M. Luquer and Heinrich Ries,[21] who have also made a study of the area, on the other hand consider it a part of the Fordham. The writer's studies in this region were not sufficiently detailed to allow him to make a positive statement, but it seems most likely from the position of these rocks with respect to surrounding limestone belts, outcrops of which occur occasionally and which are

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[19] Geologic map of New York. Lower Hudson Sheet. N. Y. State Mus.

[20] Bull. 315, U. S. Geol. Surv., pp. 344-399. 1906.

[21] "The 'Augen' gneiss area, pegmatite veins and diorite dikes at Bedford, N. Y." Am. Geol., Vol. XVIII, pp. 239-261. 1896.

undoubtedly a part of the Inwood, that these schists are a part of the Manhattan formation.

A specimen collected one-half mile southeast of Bedford Village along the road to Stamford, when examined under the microscope in thin section, shows a medium-grained crystalline texture and foliated structure. The principal minerals present are quartz, feldspar and biotite. Pyrite and magnetite occur in minor amounts. The feldspar consists of both orthoclase and plagioclase, the latter showing extinction angles up to 30° in sections at right angles to the albite lamellæ. It is probably an acid labradorite variety. The feldspar and quartz occur in irregular, fairly even-sized, interlocking grains. The biotite occurs oriented parallel to the plane of foliation and shows intense pleochroism from light yellowish to dark reddish brown. Another specimen collected one mile northwest of Poundridge shows very little variation in texture, structure or mineralogical composition from the above. The plagioclase here shows extinction angles up to 22° 30′ and is evidently andesine. A light pink garnet containing numerous inclusions of quartz and biotite is present in considerable amounts.

From the above description it will be seen that the rock is lithologically very similar to certain types of Manhattan schist occurring quite abundantly elsewhere. In this schist, however, southeast of Bedford Village, large "augen" of feldspar, usually orthoclase, which reach a length of one inch or more at times, are locally quite abundant, so that the rock becomes an "augen" gneiss. A further discussion of these "augen" will be taken up under pegmatitic intrusions in a later paragraph.

With the exception of the above occurrence of "augen" gneiss at Bedford Village, the schist does not show any petrographic feature essentially different from those already described from Manhattan Island and the region immediately to the northwest, until an outcrop occurring just north of Croton-on-the-Hudson is reached. Following north from this point along the road to Peekskill one crosses an area of the schist which is less thoroughly metamorphosed than most of the schists of the same age occurring to the south and also than those occurring one and one-half miles further north, in the vicinity of the Cortland intrusions which will be discussed later.

Just north of Croton Village, along the above road, the schist has a dark gray color and very foliated structure. In a hand specimen, it appears to be made up largely of prominent crystals of biotite imbedded in a fine shiny matrix consisting mostly of muscovite. Under the microscope, the most prominent mineral is seen to be biotite (Pl. XIII, Fig. 4). It is a deep reddish brown variety showing marked pleochroism and usually has its basal section oriented parallel to the plane of foliation but not always. The fine-textured matrix in which the biotite occurs consists of muscovite, smaller biotite flakes, quartz and iron oxides. The little flakes of muscovite and biotite are usually oriented parallel to the foliation and often curve around the larger biotite crystals.

Going north from the above locality the schist seems to show slightly more severe metamorphism. Garnet and in some cases staurolite become important mineral constituents. Tourmaline has been introduced. A specimen collected about one mile north of Croton-on-the-Hudson along the road is made up largely of a matrix of fine muscovite in which numerous garnet and staurolite crystals are imbedded. Under the microscope, the matrix is seen to be made up largely of small flakes of muscovite together with some quartz and a little orthoclase and plagioclase (Pl. XIII, Fig. 5). Most of the biotite present occurs in much larger flakes than the muscovite. A light pink garnet and a yellowish brown staurolite are quite abundant, occurring in idiomorphic crystals. For a chemical analysis of this schist see analysis 3 on page 212. This was the only place south of the Highlands where staurolite was found as an abundant constituent in the schist. It is only present elsewhere in very small amounts. The rock here has a little more coarse-grained crystalline texture than that described above.

Another specimen taken from near the same locality shows upon examination in thin section under the microscope abundant little lath-shaped crystals of dark brown tourmaline. The rock is also much more quartzose and feldspathic. The feldspar is largely plagioclase of an andesine variety, showing extinction angles up to 25° in sections measured at right angles to the albite lamellæ.

North of this area, no schist is again encountered until the southern margin of the Cortland intrusive series is reached. A belt of gneiss and limestone intervenes. A specimen of the mica schist from a point one-quarter mile west of Crugers, not far from the river and a short distance south of the contact with the diorites of the Cortland series, is seen, under the microscope, to be made up of biotite, muscovite, quartz and garnet, associated with small quantities of orthoclase and plagioclase and a little apatite. The biotite shows marked pleochroism from light yellowish brown to deep brown. It and the muscovite are often intimately intergrown with their basal sections in the plane of foliation. The irregular interlocking quartz grains are also usually elongated parallel to the schistosity. The garnet is very abundant in small crystals, rarely exceeding a diameter of .2 millimeter.

The schist northeast of Crugers along the railroad near the contact shows very much the same structure and mineralogical composition. Feldspar, mostly orthoclase, is most abundant. Some of the quartz is filled with inclusions of rutile needles. Garnet is not as abundant, but it occurs in somewhat larger grains.

Farther north, an area of schist and limestone undoubtedly belonging to the Manhattan-Inwood series adjoins the Cortland intrusives on the west at Verplanck. The schist here has a medium to fine crystalline texture and a banded rather gneissoid appearance. In thin section under the microscope, it is seen to consist largely of mica, mostly biotite, although considerable amounts of muscovite, feldspar and quartz (Pl. XIII, Fig. 3) are also present. Minor amounts of a dark brown tourmaline also occur. The biotite shows intense pleochroism from light yellowish brown to deep brown. The feldspar is mostly microcline, which is present in large amounts. The structure is distinctly foliated, due to the parallel orientation of the mica and the elongation of the feldspar and quartz grains.

Another specimen of mica schist which occurs interbedded with the limestone at Verplanck, when examined under the microscope, proves to be much less thoroughly recrystallized and metamorphosed than the above. Abundant irregular flakes of deep brown biotite occur in a very fine-grained matrix consisting mostly of quartz and sericite.

The schist again appears just north of the Cortlandt intrusive rocks. Not far from the actual contact near the southeastern corner of the town of Peekskill, several outcrops occur along the road to Yorktown Heights. The rock is medium to fine grained in texture and distinctly foliated. Under the microscope, it is seen to be made up largely of biotite, sericite and quartz. The quartz grains occurring between the parallel mica flakes are extremely fine in texture. Another specimen taken from a point nearer to the actual contact is much more crystalline in its nature and shows a higher degree of metamorphism. The minerals present are biotite, muscovite, quartz, feldspar, staurolite, garnet and a little sillimanite. Some dark brown intensely pleochroic tourmaline was also noticed.

North of this area, no further outcrops of true schists belonging to the Manhattan formation occur, but along the northwestern side of the Peekskill Creek Valley about two miles northeast of Peekskill a phyllite appears. A description of this phyllite and a discussion of its relation to the Manhattan formation will be taken up in a later paragraph.

East and southeast of Peekskill the schists representing the Manhattan formation become coarsely crystalline again and are more nearly like those occurring on Manhattan Island. In places a quartzitic variety predominates. This is made up largely of quartz, with some feldspar, biotite and muscovite and a little garnet. Some magnetite is also present. The quartz and feldspar occur in irregular interlocking grains, while the micas are oriented parallel to the foliation. Both orthoclase and plagioclase are present. The plagioclase shows extinction angles up to 9° in sections at right angles to the albite lamellæ and is evidently a variety of oligoclase. The garnet occurs in irregular grains at times full of quartz inclusions. Thin seams of very micaceous type are often interbedded with this quartzitic variety of schist. These are usually very much crenulated and contorted, while the quartzitic variety does not show these minor folds. This micaceous type consists largely of muscovite and biotite, with small amounts of quartz and a little garnet. The mica flakes curve around the garnet.

Toward the northeast, the most northerly outcrops of Manhattan schist occur in the vicinity of Brewster in southeastern Putnam County. Schists and limestones belonging to the Manhattan-Inwood series are well exposed in a cut about two miles east of Brewster along the New York and New England Railroad. The schist is rather coarsely crystalline and has a distinctly foliated structure. In thin section under the microscope, it is seen to consist principally of feldspar, biotite and quartz, together with a little tremolite, pyrite and an occasional rounded zircon grain. The feldspar is mostly plagioclase giving extinction angles up to 24° in sections at right angles to the albite lamellæ. It is probably an acid labradorite. Some orthoclase is also present, since many of the feldspars are unstriated and optically negative. The biotite shows marked pleochroism from light yellowish to deep reddish brown. The rock has undergone considerable strain. Most of the feldspar shows strain shadows and wedge twins are common. Mortar structure is also developed in the case of some of the feldspar grains, which are frequently surrounded by a border of finely granular material.

About one mile south of Brewster along the road to Croton Falls a quartzite phase of the schist is well developed. The rock here is made up of quartz, biotite, feldspar and muscovite, with quartz greatly in excess of the other constituents. Occasionally a light pink garnet is also present. The quartz is quite free from inclusions. It and the feldspar occur in interlocking grains usually elongated parallel to the foliation. The biotite is a dark greenish brown, highly pleochroic variety. More micaceous and feldspathic phases of the schist are also present at this locality, but the quartzitic type predominates. On the whole, however, the schist in the vicinity of Brewster is very closely similar to that occurring farther south.

The relation of the Manhattan schist to the underlying limestone is well shown in the excavation at present being made for the new Kensico reservoir dam at Valhalla about two miles north of White Plains in southern Westchester County. The Fordham gneiss, Inwood limestone, and Manhattan schist occur in their normal order of succession here, the gneiss making up the hills on the east, while the schist makes up those on the west of the reservoir site, with the limestone occupying the valley between the two. The formations all dip steeply toward the west.

A thin section of the Fordham gneiss taken from near the contact with the overlying limestone shows a distinctly gneissoid structure. It is made up largely of feldspar, biotite and quartz, together with a little titanite and an occasional apatite crystal. The feldspar is largely plagioclase, giving extinction angles up to 8° in sections at right angles to the albite lamellæ. It is optically positive and is evidently an oligoclase-albite variety. The biotite is an intensely pleochroic, deep brown variety. It occurs in comparatively small crystals. The greater concentration of these in particular bands gives the rock its gneissoid appearance.

In the limestone, a short distance above the contact with the underlying gneiss, an interbedded layer of gneissoid rock several feet thick occurs. Under the microscope, it is seen to be made up largely of feldspar, both microcline and orthoclase, diopside, a reddish brown variety of biotite, calcite and a little quartz. Minor quantities of titanite were also noticed.

As the contact of the limestone with the overlying schist is approached, layers of interbedded schist begin to appear in the limestone. Some of these are quite garnetiferous. A thin section of a garnetiferous mica schist occurring at this point, when examined under the microscope, was seen to consist largely of biotite, garnet, quartz, sillimanite and a little feldspar, both orthoclase and plagioclase being represented. A few rounded grains of zircon are also present. The garnet, which occasionally contains inclusions of magnetite and biotite, is a light pink variety and reaches a diameter of .5 millimeter. The sillimanite occurs in little needles in the quartz and also as a fibrous aggregate. It is abundant. The biotite is a deep reddish brown variety. The rock contains numerous small stringers of pegmatitic material. For its chemical composition see analysis 4 on page 212. Other varieties of the interbedded schist contain little or no garnet and are made up largely of a deep reddish brown biotite, quartz and feldspar, mainly orthoclase. A few small rounded grains of zircon are usually present.

The limestone adjoining these layers of interbedded schist is often impure, at times grading into an ophicalcite. A thin section of such an ophicalcite was found to consist essentially of calcite, serpentine and muscovite. The structure of the serpentine shows that it was derived from a mineral belonging to the olivine group. One piece was found in which a few small cores of the original olivine were still left unaltered. It proved to be optically negative and, therefore, must either be true olivine, with more than 12 per cent iron, or else the variety monticellite ($Mg\ Ca\ SiO_4$).

It was absolutely colorless. The serpentine to which it has altered is also colorless in thin section and grass green in the hand specimen. No other minerals occur which would indicate the presence of much iron in the original sediment from which the ophicalcite was derived, as for example, phlogopite or biotite. Therefore, it appears probable that the original mineral was monticellite.

The true Manhattan schist overlying the limestone at this point is a feldspathic micaceous variety of medium gray color. Under the microscope, it is seen to consist largely of biotite, muscovite, quartz, feldspar, mostly orthoclase, sillimanite and a little garnet. A few small rounded grains of zircon are also present. The rock has undergone considerable crushing here since the original recrystallization during metamorphism took place. This is shown by the nature of the broken quartz and feldspar crystals and to a less extent the mica. The mica also often occurs in bent crystals.

Another variation in the schist observed, especially in the southern portion of the area on Manhattan Island, and not heretofore described, appears in the form of occasional bands very rich in cyanite. These seldom reach a width of more than an inch or two, and wherever observed were parallel to the schistosity. At times, these bands are made up entirely of long prismatic crystals of cyanite associated with muscovite and quartz (Pl. XII, Fig. 3). These crystals are optically negative and show elongation parallel to the slow ray. Extinction is unsymmetrical. Their long axes are parallel to the schistosity. These bands grade into the mica schist in which the cyanite occurs associated with biotite, muscovite, some garnet and only a little quartz. Thin veinlets of introduced quartz are usually associated with the bands running parallel to the foliation. A chemical analysis of this schist is given in a later paragraph under analysis 5 on page 212.

STRUCTURAL FEATURES

The schist and underlying formations, as has already been mentioned in the introduction, occur in a series of rather closely folded anticlines and synclines usually unsymmetrical and often overturned toward the west. The axes of these folds run in a general northeast and southwest direction and in many cases have a gentle dip toward the south. In addition to these major folds, many minor folds are developed in the schist, so that at times it becomes exceedingly contorted and crinkled. As is usually the case in folded rocks of this nature, the axes of these minor folds are parallel to those of the major ones.

Most of the schist, especially the more micaceous varieties, shows a marked foliated structure. In the case of the more gneissoid varieties, this may not be so marked, but a more or less banded structure can always be made out.

As has already been pointed out in the petrographic description, the schist shows considerable variation from place to place and even in the same outcrop. Different varieties may grade into one another gradually, or the transition may be fairly abrupt. In either case, the schistosity is always parallel to the bands of varying composition.

The schist and underlying limestone, as shown by the description already given, grade into one another, and the layers of schist interbedded with the limestone near the contact have a strike and dip which are parallel to that of the actual contact of the overlying Manhattan schist with the limestone. The foliation of the schist near the contact is parallel to the bedding of the limestone.

The normal relationship of the schist to the underlying beds has frequently been obscured by faulting. In general, these faults have a strike approximately parallel to the axes of the folds, and when such is the case, the schist may be brought in contact with the gneiss, as frequently happens. East and west faults nearly at right angles to the axes of the folds also occur. Joints are well developed in the schist at many places. A nearly vertical set cutting across the folds at about right angles is well developed at several localities on Manhattan Island.

CHEMICAL COMPOSITION

The following analyses of various types of Manhattan schist made by the writer show the range in chemical composition of some of the different varieties present:

Analyses of Manhattan Schist

	1	2	3	4	5
SiO_2	46.50	68.51	50.90	45.03	74.14
Al_2O_3	24.97	15.68	30.46	33.76	23.82
Fe_2O_3	2.63	.71	1.36	None	.63
FeO	9.58	2.32	4.59	8.19	.46
MgO	3.70	1.42	1.09	2.75	.19
CaO	2.27	3.83	.93	1.85	None
Na_2O	3.55	4.62	1.96	2.22	.37
K_2O	4.34	2.49	6.86	4.62	.52
$H_2O +$	.82	.13	.49	.91	.52
$H_2O -$	.07	.01	.05	.16	.02
TiO_2	1.61	.57	1.54	1.28	.08
Total	100.04	100.29	100.23	100.77	100.75

1. Mica feldspar schist from southeast corner of Broadway and West 116th Street, New York.
2. Gray gneissoid variety from Shaft 18, Catskill Aqueduct, West 42nd Street, near Fifth Avenue, New York.
3. Staurolite mica schist north of Croton-on-the-Hudson.
4. Garnetiferous mica schist, Kensico.
5. Cyanite schist, West 120th Street, east of Amsterdam Avenue, New York.

An examination of these analyses brings out several interesting features. In all of these, except No. 2, the MgO is present in excess over the CaO and the K_2O over the Na_2O. Also the ratio of Al_2O_3 to the CaO, Na_2O and K_2O exceeds the 1:1 ratio in each of these cases. In No. 1, this excess amounts to 70 per cent; in No. 3, 147 per cent, and in No. 4, 181 per cent. In the case of No. 5, no comparison is necessary, as the amounts of K_2O and Na_2O present are practically negligible and CaO is absent entirely, while the rock contains 23.82 per cent of Al_2O_3. Such a relationship as the above could only exist in a rock which was originally of sedimentary origin.[22] The analyses, therefore, give an important clue as to the origin of these schists.

ORIGIN

As shown above, the analyses of various types of mica schist belonging to the Manhattan formation, with the possible exception of No. 2, indicate a sedimentary origin for this formation. Analysis No. 1 of the typical mica feldspar-quartz schist developed on Manhattan Island corresponds to that of a rather argillaceous shale. The same holds true for Nos. 3 and 4. No. 2, on the other hand, which is that of a gray gneissoid variety, as far as chemical composition is concerned, might be either of sedimentary or igneous origin. Its field relation, however, to the associated typical mica schist is such that it can only be interpreted as being of the same origin and merely representing a phase of deposition of somewhat different character. The clastic material from which it was derived, originating from the disintegration of an igneous rock of granitic composition, had probably been less thoroughly decomposed and sorted before deposition took place, therefore giving rise to the deposition of an arkose. It probably represents a coarser phase of deposition than any of the others which originally were undoubtedly fine muds.

The variation in texture and composition of the schist both vertically and horizontally over large areas also permits of but one interpretation, namely, a sedimentary origin. The occurrence of occasional very quartzitic beds grading into pure quartzites furnishes further corroboration toward this conclusion. The nature of the contact between the schist and

[22] Edson S. Bastin: Jour. Geol., Vol. 17, p. 472. 1909.

underlying limestone also agrees with such a view. The gradation of the limestone into schist and the occurrence of thin beds of schist in the limestone near the contact is what one would expect to find when the conditions favorable for the deposition of a limestone gradually changed toward those leading to the deposition of an argillaceous sediment. Evidently the two formations are conformable.

Later, these strata underwent profound regional metamorphism which led to the complete recrystallization of the constituents present. These changes were brought about through burial to a considerable depth underneath other sediments, followed by the inauguration of a period of great orogenic movements which brought about the intense folding of the strata involved. These orogenic movements were accompanied by a series of granitic intrusives which are described later and which also must have been important factors leading toward the thorough recrystallization of the original sediments. Their effect will be discussed in somewhat greater detail in another paragraph.

The formation of the schist, therefore, took place under mass-mechanical conditions in the zone of ana-morphism, as described by Professor Van Hise.[23] If we follow Dr. Grubenmann's plan of dividing the outer portion of the earth into three zones, based upon the nature of the metamorphic changes taking place at different depths, the formation of the schist took place in the middle zone. In this zone, as described by Dr. Grubenmann,[24] the temperature is notably higher than in the upper zone, and pressure and temperature alike tend to work toward the production of such minerals as represent the smallest molecular volumes and highest specific gravities for the constituent components present. The pressure is mostly due to stress, although hydrostatic pressure due to the superincumbent mass also begins to become effected. There is little possibility of any movement of the particles, and stress aided by temperature, therefore, works principally toward recrystallization, so that chemical action not only keeps pace with mechanical but even exceeds it. Wholly crystalline rocks are therefore formed in this zone, and good cataclastic structures are not of common occurrence. On account of the fact that the prevailing pressure is due to stress, this is the home of the schists. The characteristic minerals of this zone are muscovite, biotite, zoisite, epidote and to a lesser extent hornblende, staurolite, garnet and cyanite. Dr. Grubenmann[25] also calls attention to the well known fact that the higher the temperature and pressure under these conditions the greater will be the

[23] Monograph XLVII, U. S. Geol. Surv., pp. 685-698. 1904.

[24] Die kristallinen Schiefer. Zweite Auflage, p. 78. 1910.

[25] *Ibid.*, p. 75.

tendency of minerals rich in OH to alter to those lower in OH and finally to those free from it entirely. Chlorite will be replaced by biotite; zoisite and epidote by plagioclase, and muscovite, by orthoclase and microcline.

In the case of the Manhattan schist, it has already been seen that the biotite-quartz-feldspar varieties predominate, although muscovite is usually also present and is frequently an important constituent. These evidently represent the final stages to which metamorphism will proceed in this zone. With the exception of the area of schist to the north of Croton-on-the-Hudson and that in the vicinity of Peekskill far enough away from the Cortlandt intrusions to be out of range of very much influence from their contact metamorphic effects, the schists of the region under discussion have all undergone about the same degree of metamorphism.

In the case of the schist just north of Croton Village, it is quite evident that the fine matrix of muscovite, biotite, quartz and iron oxide in which the coarser biotite flakes are imbedded, if recrystallization had proceeded to a further stage, would have been converted into a much coarser mass consisting of larger biotite crystals, feldspars and quartz, with possibly some garnet and only a little muscovite. Further north of the same area of schist where metamorphism has been somewhat more intense, feldspar does become quite prominent. Staurolite and garnet also become quite abundant constituents of the schist here. The garnet, as seen from the petrographic description of the schist from widely distributed outcrops, is a quite common constituent of these rocks. Staurolite, on the other hand, is quite rare, this being the only place south of the Highlands where it was found in any abundance. Apparently with the more severe metamorphism which took place to the east and south, it was converted into other minerals. What has been said in regard to the schist just north of Croton-on-the-Hudson also applies to the schist occurring near the southeast corner of the town of Peekskill along the road to Yorktown Heights.

As may be seen from the petrographic description, the minerals present in the schist are quartz, orthoclase, plagioclase (ranging from oligoclase to labradorite), biotite, muscovite, garnet, staurolite, sillimanite, cyanite, magnetite, pyrite, apatite, zircon, zoisite and tourmaline. Of these, all but the tourmaline have probably resulted from the recrystallization of constituents already present in the original sediments before recrystallization took place. None of these minerals contain components which would not occur in such a formation as the one from which the schist was derived. The presence of the tourmaline on the other hand is probably due to the introduction of a least a portion of its constituents, especially the boron by emanations which accompanied the pegmatitic intrusions referred to later.

The thin seams of cyanite schist described as occasionally occurring in the mica schist on Manhattan Island are sufficiently different from the ordinary mica schist to deserve further mention. Referring back to analysis 5, p. 212, which is of such a schist, it will be seen that it is made up almost entirely of silica and alumina. If this schist had been derived from an original sediment, it would mean that there must have been a very thin layer of practically pure kaolinite and quartz where the thin seams of cyanite schist now occur. As already mentioned, it hardly ever occurs in seams over one or two inches wide. It is not very probable that such a remarkable concentration of these two constituents should occur in such narrow seams when the surrounding sediments were of such entirely different composition. What seems more probable is that some of the more soluble original constituents have been leached out by percolating waters along these seams, leaving behind the less soluble alumina probably present in the form of kaolinite. The stringers of introduced quartz associated with these seams would seem to bear out this theory. They at least indicate that such circulation has taken place. This circulation of water along these seams and the introduction of quartz was probably closely related to the pegmatitic intrusions occurring in the schist which are discussed later.

Associated Igneous Rocks

FOLIATED BASIC INTRUSIONS

Hornblende Schist

Intercalated with the mica schist of the Manhattan formation are often layers of hornblende schist which vary in width from less than a foot up to two hundred feet or more. These layers may often be followed along the strike for several thousand feet. Sometimes several of them will occur parallel to one another and separated by only a slight thickness of intervening mica schist.

The gradation from hornblende to mica schist is always a sharp one. The sheets of hornblende schist practically always occur parallel to the foliation of the schist which has been shown to be parallel to the bedding (Pl. VIII, Fig. 1). The writer did not come across a case where any marked deviation from this relationship could be detected, but Dr. Charles P. Berkey[26] has discovered an occurrence in mapping the geology of the Tarrytown quadrangle where the hornblende schist cut distinctly across the foliation of the mica schist, and Mr. John R. Healy[27] has observed a similar case in the Catskill aqueduct under Manhattan Island.

[26] Oral communication.
[27] Oral communication.

In general, however, as already shown, these sheets run parallel with the foliation of the mica schist and are just as folded and crumpled as the latter. At times, the hornblende schist is even more plicated than the mica schist. This usually occurs where the latter was a rather quartzose variety. In such a case, the hornblende schist is the more pliant member, and naturally it was more closely folded.

In a hand specimen, the hornblende schist appears rather massive, showing some foliation, however, and a tendency to cleave in parallel plates. Its color is greenish black which serves to readily distinguish it from the lighter colored mica schist. In mineral composition, it consists principally of a dark green hornblende, together with subordinate amounts of feldspar, mostly plagioclase, and quartz. Minor accessory constituents usually present are magnetite, biotite, apatite, titanite, zircon and pyrite. In some cases, garnet also occurs in it in quite appreciable amounts. This schist maintains a fairly uniform mineral composition from place to place without much variation in the percentages of the constituents present.

The hornblende schists are particularly well developed along the southern shores of Croton Lake in the vicinity of the old Croton dam. A thin section of a specimen taken from an outcrop exposed in a cut a short distance west of the bridge across the lake at this place when examined under the microscope is seen to consist largely of dark green hornblende, together with minor amounts of quartz and feldspar (Pl. XII, Fig. 4). Titanite is present in considerable amounts. Other accessory minerals are biotite, magnetite, zircon and apatite. The hornblende is a deep brownish green variety showing marked pleochroism from light greenish brown through brownish green to deep green. Prismatic cleavage is well developed. It often contains inclusions of titanite and apatite. The feldspar and quartz occur in irregular interlocking grains of comparatively small size. The feldspar is mostly plagioclase, although some of it is unstriated. It shows extinction angles up to 16° 30′ in sections at right angles to the albite lamellæ and is optically positive. It is evidently andesine. The hornblende crystals show a roughly parallel orientation which gives the rock its foliated structure. The chemical composition of this specimen of hornblende schist is given in a later paragraph.

An interesting phenomenon was noticed along a fault plane which intersected, obliquely to the foliation, the sheet of hornblende schist just described. On both walls of the fault a thin coating consisting of dark greenish brown biotite flakes was developed. Evidently during the shearing accompanying the fault movement conditions were favorable for recrystallization, and the hornblende along the fault was converted into biotite. A little secondary quartz was also introduced. The hornblende schist must still have been buried under a considerable thickness of overlying strata when this took place, as the alteration of hornblende into biotite requires rather deep-seated conditions.[28]

Small stringers of pegmatitic material are fairly numerous in the hornblende schist at this place. These usually follow the foliation of the schist, although at times they also cut across it and occasionally widen out into lenticular or irregular shaped masses. Associated with these stringers are occasionally found lenticular masses of epidote schist evidently derived by alteration from the hornblende schist. These are seldom more than six inches wide and three or four feet long (Pl. VIII, Fig. 2).

In thin section, this variety is seen to consist principally of epidote associated with remnants of the unaltered dark green hornblende. Some calcite is also present as a secondary product. Quartz appears both in little irregular shaped grains distributed through the whole mass and also in little stringers. The accessory constituents present are magnetite, titanite and zircon. A chemical analysis of the epidote schist will be found in a later paragraph. Such a rock is known as an epidosite.

Attention has already been called to the sharp contacts between the hornblende schist and mica schist. This is very noticeable wherever such contacts are exposed. Thin sections of the hornblende schist and mica schist where they adjoin were examined from two parallel hornblende schist sheets occurring in the mica schist about one and one-quarter miles northwest of Hartsdale along the road to Elmsford. The lower of these sheets is about two and a half feet thick, while the upper one is much thicker but is partially covered. Two and one-half feet of mica schist separate the two. They are involved in a sharp anticline.

The mica schist is a quartzitic variety at this place which has a medium-grained crystalline texture and foliated structure. It consists largely of quartz in irregular grains and usually elongated parallel to the foliation; of a dark greenish brown biotite showing parallel orientation and a little feldspar, mostly plagioclase; of an occasional small garnet, and of a few rounded grains of zircon. The hornblende schist is a dark greenish black rock with a more or less foliated texture. It consists principally of a dark brownish green hornblende, together with feldspar and a little quartz. Accessory constituents are magnetite, zircon, titanite and zoisite. The hornblende shows marked pleochroism from light brown through brownish green to dark green. The feldspar is mostly plagioclase, giving extinction angles up to 23° 30′ in sections at right angles to the albite lamellæ, thereby indicating an andesine.

Very little difference from the normal was noticeable in these two rocks in the specimens taken from near the contacts. Occasionally biotite be-

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[28] C. R. Van Hise: Treatise on Metamorphism. U. S. Geol. Surv., Mon. 47, p. 290. 1904.

came quite an important accessory constituent of the hornblende schist, but this mineral was present just as abundantly in specimens collected elsewhere, where they were not taken from the vicinity of any contact. In the mica schist, however, just above the lower sheet of hornblende schist, which is the smaller of the two, a dark brownish green hornblende identical with the one present in the hornblende schist was found in occasional crystals. Such a hornblende was not noticed in any other specimens of mica schist and is not a normal constituent of this rock. Apparently the presence of the hornblende schist explains its occurrence.

Closely related to the hornblende schist is a variety of hornblende or quartz diorite gneiss which occurs in the mica schist at various places but not nearly as abundantly as the hornblende schist itself. Its mode of occurrence and structural relationship are the same as that of the hornblende schist, and sometimes it grades into the latter. Megascopically it is seen to be made up of alternating light and dark bands, usually less than an inch thick, which grade into one another.

Such a gneiss occurs about three-quarters of a mile southwest of Millwood along the road to Ossining. The lighter bands, when examined under the microscope, are seen to consist largely of quartz, feldspar and hornblende, together with small amounts of biotite. A little garnet is also present, as well as an occasional zircon. Small amounts of epidote and zoisite occur as secondary minerals. A somewhat cataclastic structure has been developed. The feldspar consists of both orthoclase and plagioclase. The latter is optically positive and shows extinction angles up to 5° 30′ in sections at right angles to the albite lamellæ, which would indicate an albite-oligoclase. The darker bands owe their color to the fact that the hornblende becomes much more abundant in them, being the most important constituent. The other minerals of the lighter bands, however, are also present but in smaller amounts.

Actinolite and Tremolite Schists and Associated Types

Another type of schist occasionally found interstratified with the mica schists consists predominantly of actinolite or tremolite. This type is very similar in its mode of occurrence to the hornblende schist just described. A sheet was encountered in the Catskill Aqueduct tunnel just north of Shaft 18 at Madison Square, New York City. The borders of the sheet consist of a very coarsely crystalline biotite schist, in which biotite makes up the greater part of the rock. Most of the sheet, however, is an extremely foliated tremolite schist. When examined in thin section under the microscope, it is seen to be made up largely of tremolite, biotite and a little talc. The tremolite occurs in long acicular crystals showing good prismatic cleavage. Transverse fractures are also well developed.

The biotite is a deep brown variety with a slight tinge of red. It occurs sparingly throughout the mass between the tremolite crystals and is also concentrated in lenticular bunches averaging about .2 x .3 x 1.00 inch in size. The talc occurs in tabular flakes among the tremolite crystals. In portions of the sheet, the talc predominates and the rock grades into a talc schist. Veins of asbestiform amphibole up to two inches in width have also been developed in places. This amphibole occurs with its long axis at right angles to the foliation. The tremolite occurs in parallel orientation with the schistosity. The whole mass shows evidence of having undergone intense shearing accompanied by recrystallization of the constituent minerals into new combinations.

The mass of actinolite and tremolite schist formerly exposed at Eleventh Avenue and West 59th Street[29] is another example of this type. Here talcose and chloritic varieties, together with serpentine and ophicalcite, were also present in close association with the actinolitic and tremolitic varieties.

Harrison Granodiorite Gneiss

Another rock probably quite closely related genetically to the hornblende schist described is a granodiorite gneiss occurring in the southeastern portion of Westchester County. Its relation to the mica schist is somewhat similar to that of the hornblende schist, only it occurs in a much more extensive mass. The strike of the gneissoid to schistose structure developed in it is parallel to the foliation of the mica schist adjoining it.

This gneiss is most extensively developed just across the State line in Connecticut, where it occupies a large area. Two prongs from this mass extend southwest into Westchester County, New York. The northwestern one of these is about one and one-quarter miles wide and extends as far as Larchmont, while the southeastern one is about one mile wide and extends to Rye Point. An area of schist about one and three-quarter miles wide separated the two prongs.

Professor Heinrich Ries[30] was the first to describe this gneiss from the vicinity of Harrison in Westchester County, and it has since then been generally referred to as the "Harrison granodiorite." The Connecticut Survey[31] on their preliminary geological map of the State, however, have called it the Danbury granodiorite gneiss, correlating it with similar gneisses which are quite extensively developed in other portions of western Connecticut.

[29] A. A. JULIEN: "Amphibole schists of Manhattan Island." Bull. Geol. Soc. Am., Vol. 14, pp. 421-494. 1903.

[30] "On a granodiorite near Harrison, Westchester County, N. Y." Trans. N. Y. Acad. Sci., Vol. 14, pp. 80-86. 1895.

[31] Geol. and Nat. Hist. Surv. Conn., Bull. No. 7. 1907.

In a hand specimen, the rock shows a very gneissoid structure and medium coarse crystalline texture. The principal minerals present are biotite, hornblende, feldspar and quartz, with the ferromagnesian minerals occurring in such large amounts as to give the rock a dark color. Occasionally "augen" of feldspar are a prominent feature in the rock. These sometimes reach a length of one inch with a width of one-quarter inch.

A thin section of a specimen from north of Larchmont in Westchester County, when examined under the microscope, shows a medium coarse crystalline texture and foliated structure due to the more or less parallel orientation of the biotite and hornblende. The section consists largely of feldspar, hornblende, biotite and quartz. Magnetite, titanite and apatite are present as accessory constituents. The feldspar is largely plagioclase, which gives extinction angles up to 26° in sections at right angles to the albite lamellæ and is optically positive. It is evidently an acid labradorite. Some orthoclase is also present, much of the feldspar being unstriated. A micrographic intergrowth of feldspar with quartz is occasionally developed. Undulatory extinction in the feldspar and quartz is of common occurrence.

Another thin section made from a specimen from Greenwich, Connecticut, shows practically the same structure and texture (Pl. XII, Fig. 5). The mineral composition varies only slightly. Biotite is present in excess of hornblende. In addition to the plagioclase and orthoclase, some microcline also occurs. An analysis of this rock is given in the next paragraph.

The following analyses of hornblende schist, epidosite and granodiorite gneiss were made by the writer:

Analyses of Hornblende Schist, Epidosite and Gneiss

	1	2	3
SiO_2	45.90	43.52	55.71
Al_2O_3	15.58	16.60	19.15
Fe_2O_3	2.23	6.66	......
FeO	10.48	4.79	5.81
Mgo	7.02	3.42	4.52
CaO	11.14	19.95	6.42
Na_2O	2.47	.77	3.55
K_2O	1.19	.25	4.56
H_2O +	.20	.31	.09
H_2O —	.06	.11	.06
CO_2	......	.41	......
TiO_2	3.71	3.92	.75
Total	99.98	100.71	100.62

Norms

	1	3
Orthoclase	7.23%	27.24%
Albite	16.77	28.30
Anorthite	27.80	22.52
Nephelite	2.27	1.14
Diopside	22.32	7.55
Olivine	13.08	12.36
Magnetite	3.25	....
Ilmenite	7.08	1.54

No. 1. Hornblende schist from south shore of Croton Lake. Magmatic symbol, III, 4.4.3. Auvergnose.

No. 2. Epidote schist or epidosite from above locality.

No. 3. Granodiorite gneiss. Greenwich, Connecticut. Symbol II, 5.3.3. Shoshonose.

In the following table, analyses of massive igneous rocks very similar in chemical composition to the hornblende schist and granodiorite gneiss are given for comparison:

Analyses of Schists and Massive Igneous Rocks

	1	2	3	4	5	6	7	8
SiO_2	45.90	49.78	47.45	46.59	46.91	55.71	55.69	54.72
Al_2O_3	15.58	13.13	14.83	17.55	15.85	19.15	19.09	17.79
Fe_2O_3	2.23	4.35	2.47	1.68	2.86	......	4.07	2.08
FeO	10.48	11.71	14.71	10.46	9.95	5.81	3.26	6.03
MgO	7.02	5.40	5.00	7.76	7.01	4.52	3.41	5.85
CaO	11.14	8.92	8.87	10.64	9.62	6.42	6.87	6.84
Na_2O	2.47	2.39	2.97	3.31	2.65	3.55	2.89	3.02
K_2O	1.19	1.05	.99	.72	.69	4.56	4.41	3.01
H_2O+	.20	1.14	1.00	.07	1.62	.09	.17	......
H_2O-	.06			.10	.24	.06	......	......
TiO_2	3.71	2.22	1.47	1.41	2.03	.75	......	......
P_2O_5	......	......	......	......	.26	......	......	......
MnO	......	.27	.36	......	.22	......	......	......
CO_2	......	.10	......	......	......	......	......	......
Total	99.98	100.46	100.12	100.29	99.98	100.62	99.85	99.34

No. 1. Hornblende schist from south shore of Croton Lake.
No. 2. Hornblende schist, Scourie, N. W. coast of Scotland. J. J. H. Teall, Quart. Jour. Geol. Soc., Vol. 41, p. 137. 1885.
No. 3. Dolerite (diabase), Scourie, N. W. coast of Scotland. J. J. H. Teall, Quart. Jour. Geol. Soc., Vol. 41, p. 135. 1885.
No. 4. Camptonite, Salem Neck, Essex Co., Mass. H. S. Washington, Jour. Geol., Vol. VII, p. 285. 1899.
No. 5. Diorite, Hump Mountain, Mitchell Co., North Carolina. U. S. Geol. Surv. Bull., p. 52. 1900.
No. 6. Granodiorite gneiss, Greenwich, Connecticut.
No. 7. Biotite vulsinite, Monte Santa Croce, Rocca, Monfina, Italy. H. S. Washington, Jour. Geol., Vol. V, p. 252. 1897.
No. 8. Gabbro, S. E. corner of Salt Hill, near Peekskill, N. Y. J. F. Kemp, Handbook of Rocks, p. 72, No. 3. 1908.

ORIGIN OF HORNBLENDE SCHIST AND GRANODIORITE GNEISS

Dr. A. A. Julien[32] in a paper on the amphibole schists of Manhattan Island has given an excellent description of these rocks and their mode of occurrence. He has also taken up a detailed discussion in regard to their origin, and his conclusions have been quite generally accepted as being correct. He believes that these rocks represent metamorphosed igneous rocks of rather basic composition which were injected through fissures and spread out parallel to the bedding planes of the mica schist in the form of intrusive sheets or sills at a period prior to the folding of the latter.

The chemical composition of the hornblende schist furnishes very strong evidence in favor of its igneous origin. It is that of a rather basic igneous rock. The three analyses of massive igneous rocks, one of a diabase, another of a camptonite and a third of a diorite, which are given for comparison in a previous paragraph, correspond very closely to that of the hornblende schist. The hornblende schist from Scourie, Scotland, has a texture corresponding very closely to that of the New York hornblende schist. The diabase from Scourie, Scotland, has a diabasic texture. In mineral composition, it consists of feldspar, augite, ilmenite, apatite and small amounts of such secondary products as hornblende, chloritic minerals, quartz and pyrite. The camptonite from Salem Neck, Massachusetts, approaches the ophitic texture. The minerals present are hornblende, less pyroxene, occasional olivine, a labradorite feldspar, a little orthoclase and some magnetite and, rarely, apatite. The diorite from Hump Mountain, North Carolina, contains plagioclase, orthoclase, hornblende and minor amounts of quartz, biotite, magnetite and garnet. It is readily conceivable that rocks of such mineralogical composition upon undergoing intense dynamic metamorphism could and would be converted into hornblende schist. The augite in the case of the diabase and camptonite would naturally be converted into hornblende. Olivine would not be staple under such conditions and, if present, would disappear, entering into the composition of some other ferromagnesian mineral.

Another strong point in favor of an igneous origin for the hornblende schist is the sharp contact always found occurring between it and the mica schist, with the absence of any signs of gradation of one into the other. It has already been pointed out that wherever undoubted sedimentary contacts occur in the district no such sharp contacts are found, as for example, the gradation of limestone into mica schist or one type of mica schist into another.

[32] Bull. Geol. Soc. Am., Vol. 14, pp. 421-494. 1903.

If any evidence of contact metamorphism could be found, this would still further corroborate the igneous origin of the hornblende schist. As already mentioned, the only occurrence observed by the writer which might indicate such a contact zone was the occasional presence near such a contact of isolated hornblende crystals in the mica schist which were similar in appearance and optical properties to those of the hornblende schist.

The relation of the hornblende schist to the mica schist is such as might readily result from the intrusion of a series of sheets parallel to the bedding of the schist. Such a relation would also result if the igneous rock had been poured out as a lava flow at successive intervals during the period of deposition of the sediments from which the mica schist was derived. This would, however, necessitate the occurrence of numerous periods of igneous activity followed by periods of deposition of fine argillaceous sediments, as the sheets probably occur at various horizons in the schist over practically the whole area under consideration. The same would be true if they represented metamorphosed interbedded basic tuffs. It is much more reasonable to suppose that the igneous rock was intruded at numerous horizons in the sediments after their deposition in the form of intrusive sheets or sills. The fact that the hornblende schist does occasionally cut across the foliation or bedding further corroborates such a view. The only peculiar feature about the hornblende schist, if the above interpretation is correct, is that it has never yet, to the writer's knowledge, been found cutting the Inwood limestone. The probable explanation for this is that the limestone did not part readily along its bedding planes and the intrusive simply passed up through it along fissures which are not at present exposed.

From the foliated structure of the hornblende schist and its relation to the mica schist, it is quite evident that it was intruded into the original sediments prior to the period of folding and regional metamorphism. Both have been folded and crumpled with equal intensity and have been completely recrystallized. They now possess a marked foliated structure and a medium to coarsely crystalline texture. J. J. H. Teall[33] has described a similar hornblende schist from Scourie, on the northwest coast of Scotland, which can be traced through various stages of metamorphism into an original diabase dike. Analyses of this hornblende schist and diabase are quoted in a previous paragraph. The hornblende schist is made up of deep green hornblende, quartz, feldspar, ilmenite, sphene and apatite. The diabase consists of feldspar, augite, ilmenite, apatite and minor secondary products including hornblende, chlorite, quartz and

[33] Quart. Jour. Geol. Soc., Vol. 41, pp. 133-145. 1885.

pyrite. This rock was converted into hornblende schist by mechanical deformation accompanied by molecular rearrangement of the augite and feldspar. The changes which resulted in the formation of the hornblende schist of southeastern New York were probably very similar to those which have occurred in the case of the Scourie dikes.

The lenticular to tabular shaped masses of epidosite occasionally observed in the hornblende schist associated with small stringers of pegmatitic material represent an alteration which has occurred since the development of the foliated structure, since the remnants of unaltered hornblende in the epidosite show the same parallel alignment as those in the normal schist. The hornblende and feldspar of the original hornblende schist along these zones have been converted into epidote. This was brought about by some marked changes in chemical composition, as a comparison of an analysis of the hornblende schist with one of the epidosite developed from it will show. Such analyses are given in a previous paragraph. The change was accompanied by a partial oxidation of the iron and a very noticeable reduction in the percentage of magnesia, it being less than one-half as high as it is in the hornblende schist, with a correspondingly large increase in the amount of lime present. The alkalies almost disappeared during the alteration, while the percentages of the other constituents remained practically the same.

Dr. Julien,[34] in his study of this phase of alteration in the hornblende schist, came to the conclusion that intense local compression and strain were necessary for its development and that it was not connected with the process of change to pegmatite. This alteration does occur along minor fracture zones in the hornblende schist, but where observed by the writer, the injection of pegmatitic materials also accompanied those where alteration to epidote has taken place. It seems more plausible, therefore, to think that the circulation of the solutions which brought about the necessary chemical changes involved in this alteration did accompany the pegmatitic injections which occur in these fractured zones.

The actinolite, tremolite and talc schists occasionally found interstratified with the mica schist, especially on Manhattan Island, are very similar in their mode of occurrence to the hornblende schist just described. They undoubtedly have a similar origin, in that they represent much metamorphosed intrusive sheets of basic igneous rocks. In composition, these intrusives were probably somewhat more basic even than those from which the hornblende schists have been derived, since in order to get a metamorphic rock made up largely of such minerals as actinolite, tremolite and talc, it would be necessary to have an igneous rock high in magnesia and lime and comparatively low in silica, alumina and the alkalies.

[34] *Op. cit.*, p. 446.

The igneous origin of the Harrison granodiorite gneiss has never been questioned by those who have made a study of this rock. Its chemical composition is clearly that of a medium basic igneous rock, as a comparison with analyses of massive igneous rock of similar composition will show. Its uniformity of texture, structure and mineral composition over large areas is another point in favor of such an origin. It probably entered the older strata in the form of a large irregular laccolith and when they were shales. There was thus a period of igneous activity antedating the folding and dynamic metamorphism of the sediments. We reach this conclusion because of the very marked foliated structure, clearly of secondary origin, which has been developed in the granodiorite. The strike of the foliation is parallel to that of the mica schist which surrounds the intrusive.

MASSIVE BASIC IGNEOUS ROCKS

In addition to the highly metamorphosed foliated basic igneous rocks which occur as intrusives in the Manhattan schist, there is another series which shows only slight or no effects of dynamic metamorphism. The series appears as normal, massive, igneous rocks of basic composition and of granitoid texture intrusive in the schist and as massive serpentine derived from such rocks.

Cortlandt Series

The largest of these intrusive masses of basic igneous rocks occurs just south and east of Peekskill, covering an area of about twenty-eight square miles in the township of Cortlandt, the most northwesterly in Westchester County, from which the series has taken its name.

It consists of an igneous complex made up of a great number of different varieties of intrusive igneous rocks mostly of a basic nature which grade into one another, often by almost imperceptible transitions. G. S. Rogers in a recent paper[35] has discussed the geology of this intrusive mass in detail. He has shown that there is a centrally located norite area flanked on both sides by pyroxenites. The western pyroxenite probably continues beneath the Hudson River, since these rocks outcrop again at Stony Point. Between this western area of pyroxenites and the norites, lies a diorite area. To the extreme northeast, the basic rocks are adjoined by an area of granite. The order of intrusion seems to have been first pyroxenite, followed closely by the norites, the diorite and finally granite. It is among the basic members of the series that gradations from one into another appear, producing a large number of intermediate types.

[35] "Geology of the Cortlandt series and its emery deposits." Ann. N. Y. Acad. Sci., Vol. XXI, pp. 11-86. 1911.

Only slight evidences of dynamic metamorphism are found in the rocks of the Cortlandt series.[36] The degree varies considerably among the different types, the granite showing the least, while in the diorite appreciable effects of strain are at times discernible, although they are rarely sufficient to be perceptible in a hand specimen. These effects are most noticeable in the vicinity of inclusions of mica schist, and it is to the borders of foreign inclusions that the effects of dynamic metamorphism are usually confined. Evidently, therefore, these rocks entered after or at least toward the close of the period of intense folding, during which the shales were converted into mica schists, because, if the intrusion had taken place previous to that period, one should discover a foliated structure similar to that present in the Harrison granodiorite.

Very marked contact metamorphism has frequently occurred in the mica schist in the vicinity of the intrusions. Mention has already been made of this in describing the mica schist in the vicinity of Peekskill and Crugers. G. H. Williams[37] has given an excellent description of a contact zone from the vicinity of Crugers. The mica schist shows a constantly increasing metamorphism as the intrusive rocks are approached. Garnet becomes very abundant, and other contact metamorphic minerals such as sillimanite, cyanite and staurolite make their appearance.

The inclusions of schist in the igneous rocks themselves naturally also show the effects of contact metamorphism. G. S. Rogers[38] has come to the conclusion that the emery deposits which appear at several localities in the Cortlandt series are due to the more or less complete absorption of such inclusions by the intrusive magma before it solidified.

Croton Falls Hornblendite

A similar but smaller area of basic intrusives having very much less variation in composition occurs in the vicinity of Croton Falls. This mass is about two and a half miles long and one-half mile wide starting in at a point a little south of Croton Falls and extending in the form of a ridge in a northeasterly direction on the east side of the Croton River.

The rock at the northeastern end of this area is a massive dark green coarsely crystalline hornblendite. Some biotite is also visible in the hand specimen along with the hornblende. In thin section, under the microscope, it shows a coarse granitoid texture. In mineral composition,

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[36] G. S. Rogers: *Op. cit.*, pp. 54-55.

[37] Am. Jour. Sci., 3rd ser., Vol. XXXVI, pp. 254-269. 1888.

[38] *Op. cit.*, p. 81.

it consists principally of a dark green hornblende and minor amounts of dark brown biotite. Titanite, magnetite and a little pyrite appear as accessory minerals. The hornblende shows marked pleochroism from yellowish brown through greenish brown to deep green. The biotite also exhibits intense pleochroism from light yellowish brown to deep brown. This biotite hornblendite represents the typical composition of the intrusive mass at the northeast end of the area.

Along the eastern margin, the contact of the hornblendite with the mica schist may be observed at several places. At one point several apophyses of hornblendite were noticed extending into the schist. Some of these retain the coarse crystalline texture of the main mass, while others are somewhat finer grained. A thin section of this finer grained type under the microscope shows medium granitoid texture and massive structure. It consists almost entirely of hornblende with marked pleochroism from light yellowish brown through greenish brown to dark brownish green. It has well developed prismatic cleavage. A little plagioclase and titanite are present as accessory constituents.

A short distance to the east of this occurrence, several sheets of hornblende schist similar to those already described occur interstratified with the mica schist. This rock shows a distinct foliated structure. When examined under the microscope, it is seen to consist largely of a deep green hornblende, feldspar and a little quartz. The accessory minerals are magnetite, biotite and apatite. The hornblende shows marked pleochroism from light yellowish brown through greenish brown to deep green and has well developed prismatic cleavage. It does not show good crystal boundaries but occurs in irregular grains interlocked with the feldspar and quartz. These grains are usually oriented parallel to the foliation. The feldspar is chiefly plagioclase giving extinction angles up to 26° in sections at right angles to the albite lamellæ and is evidently an acid labradorite. Unstriated feldspar also is present. The feldspar grains are irregular in shape and usually elongated parallel to the foliation, but they do not show any crystallographic orientation. It is quite evident that this rock has had a different history from that of the apophyses of hornblendite occurring in the schist. The former was intruded prior to the period of folding, while the latter either at the close or else after it had ceased entirely.

At the southwestern end of the area, the hornblendite in places grades into a diorite. A section of the typical hornblendite as developed here was made from a specimen taken from the east side of the railroad at about one-quarter of a mile south of Croton Falls. It is a massive dark green biotite hornblendite. In thin section, it shows a coarse granitoid texture. The principal mineral present is a dark green hornblende associated with minor amounts of dark brown biotite. Small amounts of feldspar, both striated and unstriated, and a very little quartz occur in addition to the above, together with such accessory minerals as magnetite, apatite and titanite. Some of the hornblende is full of little quartz inclusions. Considerable evidence of strain is present in the section in the form of undulatory extinctions and wedge-shaped twins in the feldspar.

On the west side of the track in the same cut, the rock has taken on the composition of a diorite. The feldspar and hornblende appear in about equal amounts. Most of the rock is massive, but some of it shows a slightly foliated structure. In thin section, the texture is granitoid. The principal minerals present are a feldspar, a deep green hornblende and a dark brown biotite, together with minor amounts of magnetite, apatite and titanite. The feldspar is mostly plagioclase, giving extinction angles up to 22° 30′ in sections at right angles to the albite lamellæ, which would indicate andesine. Some orthoclase also is present, as much of the feldspar is unstriated and optically negative.

A number of inclusions of a schistose rock occur in the diorite at this place. Their contacts with the latter are usually quite sharp. A thin section of one of these, which forms a tabular, nearly vertical mass about four feet wide, shows a marked foliated structure and medium-grained crystalline texture. The principal minerals present are biotite, hornblende, feldspar and a little colorless pyroxene. Magnetite, apatite and titanite are accessory constituents. The hornblende is a deep green variety showing marked pleochroism from yellowish brown through brownish-green to deep green. The biotite shows intense pleochroism from light yellowish brown to deep brown. The feldspar is mostly plagioclase, giving extinction angles up to 20° 30′ in sections at right angles to the albite lamellæ, and is evidently an andesine. Another section from a somewhat similar inclusion also shows a marked foliated structure. A dark green hornblende is the principal mineral, associated with which are deep brown biotite and minor amounts of apatite, titanite and pyrite.

In the railroad cut at Croton Falls itself, a dark nearly black foliated rock is exposed. It has a medium coarsely crystalline texture. The thin section reveals a deep green hornblende with well developed prismatic cleavage, deep brown biotite and plagioclase. The accessory minerals are magnetite and titanite. Farther north in the same outcrop, the structure becomes even more foliated. A thin section from a specimen taken near the northern end of the cut shows a marked schistose structure. The minerals making up the rock are deep green hornblende with well developed prismatic cleavage, deep brown biotite, pale green augite and feldspar. The feldspar is mostly plagioclase, an andesine, with extinction angles up to 22° in sections at right angles to the albite lamellæ. It is optically positive. Feldspar is occasionally contained in the augite as inclusions. Titanite, apatite and magnetite occur as accessory constituents.

This area of foliated diorite gneiss apparently represents an intrusion of rather basic igneous rock which entered prior to or else during the early stages of the period of folding which involved the whole region. The hornblendite, on the other hand, was intruded during the latter stages or else after folding had ceased entirely. There are, therefore, two periods of igneous intrusion of rocks very similar in composition represented. The inclusions of diorite gneiss in the diorite itself south of Croton Falls are in accord with such a hypothesis. The hornblendite intrusions at Croton Falls were probably contemporaneous with that of the Cortlandt series at Peekskill. The hornblendite is in turn cut by a number of large dikes of granitic composition, sometimes reaching a thickness of two hundred feet or more. These range from true granite to coarse pegmatites, a variation of texture which often appears in the same dike within a very short distance. A discussion of these granitic intrusives will be taken up later. Reference is made to them here to show that the entrance of the hornblendite took place prior to the granite.

Diorite Dikes in the Vicinity of Bedford

Two occurrences of diorite in the form of dike-like intrusions have been described by Professors Luquer and Ries from the vicinity of Bedford in their paper on the geology of this region.[39] One of these occurs along the Bedford-Long Ridge Road about two and one-half miles southeast of Bedford. The rock has a dark color, medium, coarsely crystalline texture and massive structure. In thin section, one observes deep green hornblende, showing good prismatic cleavage, pale green augite and feldspar. Most of the feldspar is unstriated but is optically positive and therefore plagioclase. Titanite and apatite occur as accessory constituents. The augite apparently crystallized out before the hornblende, but the two are very intimately intergrown. Both minerals are perfectly fresh. Some of the feldspar has undergone slight alteration to an aggregate of quartz, sericite and calcite.

A similar rock occurs about two and one-quarter miles south of Bedford. It also has a dark green color, medium coarsely crystalline texture and massive structure. A thin section reveals light green hornblende

[39] Am. Geol., Vol. XVIII, pp. 239-261. 1896.

with good prismatic cleavage, dark reddish brown biotite and feldspar. The feldspar is mostly plagioclase, giving extinction angles up to 16° 30′ in sections at right angles to the albite lamellæ. It is probably andesine. A little microcline is also present. Much of the feldspar has been altered to an aggregate of kaolin, sericite and quartz. Inclusions of biotite occur both in the feldspar and amphibole, especially in the former. Apatite, magnetite and a little titanite are present as accessory constituents. A little pyrite forms an introduced mineral. In the edge of the mass, the rock becomes very much finer grained. In thin section, however, one still finds the granitoid texture. About equal amounts of light green hornblende and dark brown mica are present. The other important constituent is a plagioclase feldspar, evidently andesine, as it gives extinction angles up to 20° 15′ in sections at right angles to the albite lamellæ. Some orthoclase also occurs, together with minor amounts of apatite, titanite and magnetite.

Several other occurrences of diorite were observed in the area south of Bedford. Sheets of hornblende schist are also quite numerous in this vicinity, and the evidence again indicates that the intrusion of basic igneous rocks took place at more than one period.

Serpentine

Serpentine is associated with the Manhattan schist at several places in the area under discussion. These areas of serpentine are very similar to the massive basic intrusive rocks just described, both in their mode of occurrence and in their relations to the mica schist. D. H. Newland,[40] who has made a rather detailed study of them, has shown that they were derived from basic intrusives, probably peridotites, which have undergone serpentinization.

The largest of these serpentine masses underlies the northern portion of Staten Island. Smaller areas occur at Hoboken, New Rochelle and Rye. Newland, in his study of the Staten Island serpentine, came across unaltered remnants of olivine in some of his sections, showing that the serpentine was derived from an olivine-bearing rock. The writer has also noticed similar remnants of olivine in several sections from this locality. A thin section of the dark green massive serpentine from near the northern end of the area at Rye was also examined under the microscope. It consists of antigorite, bastite, some calcite, iron oxides, a very little tremolite and a few remnants of unaltered olivine, with a green spinel or pleonaste and magnetite as minor accessories. The bastite was

[40] School of Mines Quart., Vol. XXII, pp. 307-317 and pp. 399-410. 1901.

apparently derived from a pyroxene, while the antigorite represents altered olivine, as it shows the typical mesh structure and occasionally contains cores of unaltered olivine. Some of the serpentine from the same locality has a slightly banded structure. A thin section of this phase shows a distinctly foliated structure under the microscope and consists largely of tremolite oriented parallel to the foliation, with antigorite filling in the space between its prisms as well as the little crevices and cracks throughout the section. The tremolite is perfectly fresh and shows no alteration to serpentine. Some calcite is also present in the section. The accessory minerals are fairly abundant pleonaste and magnetite.

As has already been pointed out, these serpentine masses undoubtedly represent altered basic intrusive rocks rich in olivine. From their massive structure, it would appear that they entered either toward the close of the period of folding or after it had come to an end. They are, therefore, probably closely related to the Cortlandt series, the Croton Falls hornblendite and the Bedford diorite which have already been discussed.

Views with regard to the alteration of peridotites and allied olivine rocks to serpentine have changed considerably in recent years. It was formerly thought that the alteration was brought about by the processes of weathering, but now it is quite generally believed to be deep-seated.[41] Heated waters probably following closely upon the intrusion of the magma itself and given off by it during solidification, it is thought, have brought about the alteration of the olivine to serpentine while still buried at considerable depths.

Hornblende Porphyrite

A dike of hornblende porphyrite crosses the granites and pegmatites in a large cut just north of Springdale, about four and one-half miles out of Stamford on the New Canaan branch of the New York, New Haven and Hartford Railroad. As this is the only occurrence of a basic intrusive which is clearly of later age than the granitic intrusives in the area studied, a brief description of it will not be out of place.

The dike is about three and one-half feet thick at its widest part but is quite variable. The strike of the dike is about N. 48° E., and the dip is practically vertical. In a hand specimen, it shows a felsitic texture and dark green color. When examined in thin section under the microscope, the texture is apparently ophitic, but the space between the feldspar laths is occupied by hornblende instead of augite. The rock con-

[41] Ernst Weinschenk: Allgemeine Gesteins-kunde als Grundlage der Geologie, pp. 119-121. 1902.

sists essentially of plagioclase feldspar and hornblende, with magnetite, apatite and a very little biotite as accessory constituents. The plagioclase gives extinction angles up to 28° in sections at right angles to the albite lamellæ and is apparently an acid labradorite. The hornblende is a green variety occasionally showing typical prismatic cleavage. It occurs in small grains between the feldspar laths, and these are frequently encroached upon by it so that the crystallographic boundaries of the feldspar are not clean-cut. This would suggest that the space between the latter might originally have been occupied by augite which had afterwards altered to hornblende. No traces, however, of augite were noticed in the section, and the hornblende in all other respects has the appearance of being primary.

ACIDIC INTRUSIVES

In addition to the basic intrusives already discussed, there are other types which are of granitic composition varying from true granites to very coarse pegmatites and occurring as dikes, intrusive sheets and lenticular masses injected parallel to the foliation of the schist. The sheets and lenticular masses are far more abundant than the dikes. They appear in one form or another in nearly every outcrop of mica schist. Large masses of granite in bosses and batholiths outcrop, especially in Connecticut just beyond the New York line, where they become quite abundant. The Connecticut Geological Survey has given them the name Thomaston[42] granite.

Thomaston Granite

As typically developed, the Thomaston is a light colored biotite granite of medium to fine grain. It consists essentially of feldspar, quartz, biotite and muscovite. At many places, it shows practically no gneissic structure, but at other places is quite strongly foliated.

The granite covers a large area in the vicinity of New Canaan. It is well exposed in a railroad cut about one-half mile south of New Canaan on the New Canaan branch of the New York, New Haven and Hartford Railroad. It is a light pink massive granite with medium-grained texture. When examined in thin section under the microscope, it shows a granitoid texture and consists of microcline and a little plagioclase. A perthitic intergrowth of orthoclase and plagioclase may be occasionally noticed. Apatite and zircon are present as accessory constituents. Some of the feldspar has undergone slight alteration to kaolin and sericite, while a little chlorite is developed on some of the biotite.

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[42] Preliminary geological map of Connecticut. Conn. Geol. and Nat. Hist. Surv. Bull. No. 7. 1907.

Farther south along the same railroad, just north of Springdale, another large cut has been made in this same granite. The granite has a coarse pegmatitic texture in places, although much of it remains normal, medium-grained granitoid. The gradation from one into the other is a gradual one. It contains several inclusions of a basic igneous rock. These are usually massive and have a coarse crystalline texture and dark green color. A thin section made from one of them shows a granitoid texture and consists of green hornblende with good prismatic cleavage and deep brown biotite. A little titanite is present as an accessory constituent. The space formerly occupied by feldspar is now filled with an aggregate of calcite, quartz and other secondary products.

The gneissoid phase of the Thomaston granite is well shown in the vicinity of the Stamford reservoir, south of North Stamford. The locality is near the western border of the New Canaan mass and inclusions of schist are a prominent feature. It is to these that the banded structure of the gneiss is partially due.

Several smaller bosses of a similar granite occur to the west. One of the largest is just west of Pelhamville in the vicinity of Mount Vernon. The rock has a light gray color with a distinctly gneissoid structure and medium-grained crystalline texture. Under the microscope in thin section, it is granitoid and consists of microcline, quartz, orthoclase, some biotite and muscovite and a little plagioclase. Apatite is the principal accessory constituent.

Aplites and Pegmatites

Closely related genetically to the granites just described are a large number of intrusive sheets and dikes varying in texture from medium granitoid to very coarsely pegmatitic. Of these the intrusive sheets and lenticular masses injected parallel to the foliation of the mica schist are the most abundant. They appear in nearly every outcrop of the schist. Sometimes the injections are so numerous that the schist takes on a gneissoid appearance and becomes an injected gneiss (Pl. X, Fig. 1). They vary greatly in size from sheets 50 feet or more in thickness to those less than an inch thick. The same is true of the lenticular masses. The intrusives which are parallel to the foliation of the mica schist are often involved in all the intricate folds which have been developed in the latter.

The dikes of granite and pegmatite, on the other hand, cut across the foliation. They also cut the intrusive sheets and lenses and likewise each other, showing that they did not all enter at one time but that some are later than others. They also vary greatly in size. In some cases, as at Bedford Village, they reach a width of over two hundred feet, while in other cases they only have a thickness of a fraction of an inch.

In mineral composition, they vary from true granites and aplites in the case of the medium-grained varieties to nearly pure quartz veins in the case of the pegmatitic types. In the pegmatites, the greatest variation in mineral composition is found. They range from coarse-grained granite to pure quartz. In addition to the orthoclase, plagioclase (either albite or oligoclase), quartz, muscovite, biotite and black tourmaline which are most frequently present, a great many other more unusual minerals are sometimes available for the collector. Among these, the following have been identified by various mineralogists: amphibole, apatite, antunite, beryl, chrysoberyl, columbite, cyanite, cyrtolite, dumortierite, garnet, ilmenite, iolite, monazite, pinite, titanite, uraconite, uraninite, uranotile, xenotime and zircon.

In texture, these pegmatites are often very coarse. Feldspar crystals may reach a length of several feet, as in the case of the Bedford dikes, and many of the other accompanying minerals will have a correspondingly large size.

Some interesting structural features are also developed in the pegmatites at times. Very coarse pegmatite may often be associated with medium-grained granite in the same dike or sheet. The gradation from the one into the other may be a gradual one or it may be quite abrupt. Where such relations occur between granite and pegmatite, the former appears to have been intruded first and to have been followed closely by the latter, sometimes before the first had had an opportunity to completely solidify. Often the granitic phases in the case of the intrusive sheets show an original gneissoid structure.

A banded structure very similar to that sometimes seen in true veins is also developed (Pl. IX, Fig. 2). In instances, this structure is due to the growing inward from the walls of crystals of some of the minerals present, very often the muscovite. At other times, it is due to the progressive increase in size of the crystals of the mineral constituents from the walls inward. It may also be brought about when the intrusion of a granite or aplite is closely followed by the injection of pegmatite along the same fissure and before the former has had an opportunity to cool and completely solidify.

In the above description, it has been assumed that the pegmatites are of igneous origin, a view now quite generally accepted by geologists.[43] It is thought that they represent the final products of crystallization of rock magmas. They are the "mother liquor" so to speak, containing the bulk

[43] W. C. Brögger: Syenit Pegmatitgänge der süd norwegischen Augit und Nephelinsyenite. Zeits. f. Kryst. u. Miner., Vol. 16, pp. 215-235. 1890.
Joseph P. Iddings: Igneous Rocks. Vol. I, pp. 273-276. 1909.
Alfred Harker: The Natural History of Igneous Rocks, pp. 293-299. 1909.

of the water, boric, carbonic and hydrosulphuric acids, the fluorides, chlorides and borates of the alkali metals and of the rare earths along with some of the silicates, free silica and other oxides which remain behind after the greater portion of the magma itself has solidified. This "mother liquor" is later extruded through fissures developed in the cooling mass and the pegmatites are, therefore, found as dikes in the igneous rock from which they were derived and in the adjacent wall-rock.

The exceedingly coarse crystalline texture and accompanying structures of the pegmatites are due to the presence of the gases and mineralizers in the magma from which they crystallized. Just what per cent of the entire amount of the residual magma they represent is hard to say. Professor Iddings[44] states that the proportion of gas present probably does not amount to more than ten times that present in the original magma from which the pegmatitic "mother liquor" was differentiated. From this it varies greatly down to cases where it is the same as the parent magma. A medium-grained granite or aplite then results.

The pegmatites of southeastern New York State are undoubtedly related genetically to large batholithic masses of intrusive granite. It is highly probable that the large areas of granite previously described which have been so extensively uncovered by erosion in western Connecticut represent these intrusive masses. The area farther to the west is very likely also underlain by other batholiths which have not yet been exposed except in an occasional projecting knob. Where the granite appears at the surface in western Connecticut, it often passes, as already mentioned, into coarse pegmatite. The transitions can best be explained by imagining the pegmatites to be injected into overlying but only partially cooled and solidified portions of the original magma. The two would then be very closely related. Also as these granite areas of western Connecticut are approached, the pegmatitic sheets and dikes become very abundant and of extensive size, indicating that there must be some common genetic relation between them.

The granitic intrusions just described probably accompanied the great orogenic movements which resulted in the intense folding of the rocks of this region, including the Inwood limestone and Manhattan schist. Such periods, as Professor C. R. Van Hise[45] has pointed out, are very favorable for the entrance of igneous rocks. The relations of the intrusive sheets and injected lenses of pegmatite and granite to the mica schist are such that they must in many cases have penetrated the older rocks before the period of folding had come to an end. The sheets and lenses are often as

[44] *Op. cit.*, p. 276.
[45] "Earth Movements." Trans. Wis. Acad. Sci. Arts and Letters, Vol. II. 1898.

intricately folded as is the schist itself. On the other hand, they do not show much evidence of having come in prior to the folding since; had that been the case, evidences of considerable crushing and recrystallization of the coarse pegmatite would be expected. The crushing and recrystallization, however, fail, as the texture of the sheets and lenses is practically the same as that of the dikes which were intruded later and which are not involved in the folds. It seems reasonable, therefore, to believe that the first intrusions of granite and pegmatite accompanied the period of folding itself.

In the case of the Manhattan schist, the shales which were converted into mica schist during this period of folding yielded most readily along planes parallel to the bedding and naturally the early intrusions followed these lines of weakness, giving rise to the intrusive sheets and injected lenses which were drawn out and pinched off during the folding. In the case of the Inwood limestone, conditions were somewhat different. This was a more massive formation, and the bedding planes were not particular lines of weakness. Very few intrusives entered parallel to them. The magma rose through fissures and gave rise to true dikes where it solidified. These dikes are usually of fairly large size when they do occur, but they are not as abundant as in the mica schist (Pl. IX, Fig. 1).

The intrusive activity continued during a long interval of time, extending even beyond the period of folding. The later intrusions took the form of dikes which often cut one another, showing that some came in earlier than others, thus emphasizing the fact that igneous manifestations continued for a long time after the folding had ceased. The relations are not surprising because the pegmatites represent the final differentiation products of the great masses of granite.

In the case of igneous intrusions so richly supplied with water and other mineralizers as the pegmatites must have been, rather marked contact metamorphic effects would naturally be expected, especially in the case of the limestones. In their field occurrence, however, this does not appear to be the case. The dikes of pegmatite ten feet or more thick, apparently have produced no contact metamorphic effects on the limestone whatever. The explanation for this may be the one which Dr. E. Weinschenk[46] has given, namely, that when the pressure at the time of the intrusion is sufficiently great the CO_2 of the calcite and dolomite does not have an opportunity to escape, and hence the silica cannot combine with the lime and magnesia to form silicates. Occasionally the schist in immediate contact with the pegmatite becomes very rich in garnet. These contact phases of

[46] Grundzüge der Gesteinskunde, I Teil, p. 105. 1902.

the schist usually have also a very high content of feldspar, a portion of which was undoubtedly derived from the pegmatite. Cyanite occasionally appears, in long bladed crystals having a slight bluish tinge, in portions of the schist which have been thoroughly saturated with pegmatitic material. In this case, it is apparently of contact metamorphic origin. Undoubtedly the pegmatites derived a portion of their constituents from the rocks through which they were intruded. Such minerals as garnet and biotite probably owe their origin to this source. Black tourmaline similar in every respect to that found in the pegmatite itself often occurs in the mica schist in the vicinity of the pegmatitic intrusions and has evdently resulted from the emanations from this source.

That these granitic and pegmatitic intrusions played a very important role in the metamorphism and recrystallization of the original shale of the Manhattan formation into mica schist, there can be but little doubt. Most of the water associated with the intrusions must have been given off when solidification occurred, since it does not enter into the composition of any of the resulting minerals to any extent. This water must have been very effective in bringing about recrystallization. The local temperature must also have been raised by these intrusions. Edson S. Bastin[47] in his study of the Maine pegmatites has come to the conclusion that they crystallize at a temperature in the neighborhood of 575° C. The New York pegmatites are very similar to the Maine occurrences. These intrusions must, therefore, be regarded as very effective agents in the metamorphism of the original shale into mica schist. Other influences were the deep burial beneath overlying sediments and the severe folding and crumpling which followed the deposition of the original sediments.

Bedford "Augen" Gneiss

In discussing the mica schist in the vicinity of Bedford Village, mention has already been made of the "augen" gneiss which is so frequently associated with it. The region in which the structure occurs covers an ovoid area southeast of Bedford Village. The long axis extends in a northeast-southwest direction and has a length of about six miles. The width does not exceed two and one-half miles.

The "augen" structure is developed in two types of rock, a mica schist and a hornblende schist, but the entire area does not have the "augen" structure. It appears in bands usually parallel to the foliation. The bands grade into the ordinary schist by the gradual disappearance of the "augen" (Pl. X, Fig. 2). Sometimes the "augen" stop rather suddenly,

[47] U. S. Geol. Surv. Bull. No. 445, p. 45. 1911.

while at other times they drop out very gradually, so that the gradation from schist into "augen" gneiss is an almost imperceptible one. The width of these belts varies from those less than a foot to those several hundred feet wide.

About two-thirds of a mile southeast of Bedford Village along the road to Stamford, the "augen" gneiss is associated with a mica schist. In thin section under the microscope, the schist shows a moderately fine crystalline texture and a distinctly foliated structure. It consists chiefly of quartz, biotite and feldspar. The biotite is a deep reddish brown and is oriented parallel to the foliation. The feldspar is mostly plagioclase which gives extinction angles up to 30° in sections at right angles to the albite lamellæ. It is optically positive and is evidently an acid labradorite. Some microline is also present. The quartz and feldspar occur in irregular interlocking grains sometimes elongated parallel to the foliation. Pyrite and a little apatite are also present.

The "augen" of the gneiss consist of a pink feldspar twinned on the Carlsbad law and reaching a length of over an inch. They are very often rectangular in outline, although the ends are usually rounded. At other times, they take on an elliptical shape. The long axes are usually oriented parallel to the foliation, although not always so. "Augen" of white feldspar showing albite twinning are also present, but they do not reach as large a size as the pink ones. These give extinction angles up to 13° in sections at right angles to the albite lamellæ and are probably albite. Beside the feldspar, fairly large grains of quartz sometimes appear in veinlets with finer feldspar. In thin section, the pink feldspar is seen to be mostly microline. At times it exhibits a perthitic intergrowth with plagioclase. Quartz is seen in little veinlets throughout the rock. It sometimes contains inclusions of rutile. The finer matrix of the "augen" gneiss is very similar to the mica schist already described. It consists of quartz, a deep brown biotite, feldspar, mostly microline, and a little magnetite. The structure is distinctly foliated. The "augen" gradually disappear at the outer margins of the belt of "augen" gneiss which grades into the schist. Where typically developed the "augen" constitute a large percentage of the entire mass of the rock.

Another specimen of the "augen" gneiss taken from a belt along a road about one mile south of Bedford shows only a pink feldspar which is nearly always twinned according to the Carlsbad law. The feldspar is not as abundant as in the occurrence described above but is similar in size, shape and orientation (Pl. XI, Fig. 1). Small veinlets of pegmatitic material parallel to the foliation are present. "Augen" of feldspar are occasionally associated with these. In thin section, the matrix in which the feldspar "augen" are imbedded has a medium-grained crystalline texture and distinctly foliated structure. Its minerals are quartz, biotite, some feldspar, mostly microcline, and a little plagioclase. Apatite occurs as an accessory constituent. Many little veinlets of introduced quartz parallel to the foliation are present with which the feldspar "augen" are sometimes associated. These feldspar "augen" consist of orthoclase and microcline and sometimes show a perthitic intergrowth with plagioclase.

About two miles south of Bedford along an east and west road, there is an interesting outcrop which exhibits a transition from a true pegmatitic sheet parallel to the foliation, into "augen" gneiss and finally into mica schist with only a few "augen" of feldspar. Plate XI, Fig. 2, shows a specimen in which prominent "augen" of pink feldspar are developed along little pegmatitic stringers with which the schist is thoroughly injected.

About one and one-half miles northeast of North Castle, the "augen" structure is developed in a hornblende schist. This is a black more or less foliated rock. In thin section, one observes plagioclase, dark green hornblende with good prismatic cleavage and deep brown biotite. The plagioclase gives extinction angles up to 12° in sections at right angles to the albite lamellæ and is therefore oligoclase-andesine. Apatite is an abundant accessory constituent. Magnetite and a little titanite are also present. The "augen" show very much the same characteristics as those already described. They consist of orthoclase and some microcline. In one case, a micrographic intergrowth of orthoclase and quartz was noticed. The bands of "augen" gneiss here have very much the same relation to the hornblende schist as the others did to the mica schist. In this case, the matrix in which the "augen" occur consists essentially of the same constituents as the hornblende schist.

Professors Luquer and Ries,[48] in their study of this "augen" gneiss, came to the conclusion that it represents a metamorphosed igneous rock of the composition of a granite or aplite. The metamorphic action, they thought, produced the gneissoid structure by pressure and a granulation of the minerals, the unsheared portions of the rock remaining as "augen."

A chemical analysis made by the writer of the "augen" gneiss described from the outcrop along the road two-thirds of a mile southeast of Bedford Village along the road to Stamford gave the following composition:

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[48] *Op. cit.*, p. 205.

Analysis of Augen Gneiss

	Per cent
SiO_2	67.02
Al_2O_3	13.96
Fe_2O_3	2.36
FeO	2.73
MgO	1.27
CaO	2.69
Na_2O	3.61
K_2O	5.27
H_2O +	.36
H_2O —	.02
TiO_2	1.41
Total	100.70

Norm

	Per cent
Quartz	19.08
Orthoclase	31.69
Albite	30.39
Anorthite	6.12
Diopside	5.74
Hypersthene	1.26
Magnetite	3.48
Ilmenite	2.62
Total	100.38

Magmatic symbol II. 4.23. Adamellose.

The analysis would rather seem to uphold the above conclusions as it corresponds to that of an igneous rock of about the composition of a quartz monzonite.

There are other features, however, which cannot very well be explained by such a hypothesis. The occurrence of the "augen" gneiss in bands of varying width and their gradation into mica schist or hornblende schist cannot very well be explained by such a supposition. The fact that where the "augen" gneiss is associated with mica schist, its matrix has the composition of the mica schist and where, with hornblende schist, that of the hornblende schist, does not favor such a conclusion. If the "augen" gneiss represents a metamorphosed igneous rock in which the feldspar "augen" represent original unsheared feldspar crystals, the original rock must have had a very coarse granitoid texture or else a porphyritic texture in which the phenocrysts were feldspar. In either case, it is hard to see why these "augen" of feldspar should have their present distribution in local belts through the rest of the rock. It is also hard to account for such a variation in matrix as is represented in different places.

The apparent gradation of a pegmatite sheet into "augen" gneiss by a thorough injection of the adjoining schist with pegmatitic material, and the final gradation of this into true schist with only a few "augen" of feldspar, suggests that the "augen" gneiss represents sheared zones of schist which have been thoroughly injected and permeated with pegmatitic material consisting largely of potash feldspar together with some plagioclase and quartz. The only peculiar feature, assuming that this is the correct explanation, is that the feldspar took on a more or less crystalline outline. That this injection belonged to the earlier stages of the pegmatitic intrusions is shown by its relationship to the other schist and the later pegmatitic intrusions.

The frequent association of these feldspar "augen" with little veinlets of secondary quartz and pegmatite favors such a hypothesis. The fact that micrographic and perthitic intergrowth are occasionally present in the orthoclase and microcline also points toward such an origin as such intergrowth would hardly be expected in feldspar representing phenocrysts of a sheared porphyry. The variation in the mineral composition of the matrix can also be explained on this basis, as it would be that of the sheared rock into which the injection took place.

Occurrence of Zeolites in the Manhattan Schist

Zeolites are occasionally found lining cavities and small crevices in the Manhattan schist. Among them, thomsonite, natrolite, analcite, chabazite, phacolite, harmatome, heulandite and stilbite have been reported from Manhattan Island.[49]

Specimens of stilbite and chabazite occurring in the Manhattan schist in this manner were given to the writer by Mr. J. R. Healy, assistant engineer with the New York Board of Water Supply. They were obtained from Shaft 15 of the Catskill aqueduct at 65th Street and Central Park West. The crystals of stilbite and chabazite lined the walls of a small open crevice which followed the plane of schistosity of the mica schist for a short distance. The stilbite has a honey-yellow color and has crystallized in sheaf-like and radiated masses. The chabazite is white in color and has a nearly cubic form. It precedes the stilbite in order of crystallization, as the latter sometimes grows on top of it. Little veinlets of pegmatitic material and epidote occur in the schist closely associated with the stilbite and chabazite.

When examined in thin section under the microscope, it is seen that much of the biotite of the mica schist has been altered to chlorite. The orthoclase of the little pegmatite stringers is also much kaolinized. Associated with these pegmatitic stringers but later in origin are veinlets of quartz, which, under the microscope, appear as a fine mosaic of little grains. Veinlets of epidote with a little accompanying calcite are often associated with these quartz stringers and cut them in such a way as to show that they were the last to be introduced.

The formation of the zeolites probably accompanied the last stages of the pegmatitic intrusions. The zeolites were probably deposited by

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[49] B. B. CHAMBERLIN: "The Minerals of New York County." Trans. N. Y. Acad. Sci., Vol. VII, No. 7. 1888.

the accompanying heated waters in little crevices which had been developed after the period of folding had come to an end. In the modern view,[50] zeolites are believed to have been deposited by heated waters accompanying the last stages of igneous activity. The mere leaching of the necessary constituents by surface waters in the belt of weathering is not considered sufficient. Professor Brögger[51] has also described zeolites from pegmatite dikes where they occur as products of the last stages of crystallization.

Summary

The Manhattan schist is a series of much metamorphosed argillaceous and sandy shales, argillaceous sandstones and arkoses which represent a thickness of several thousand feet. The argillaceous sediments were laid down conformably upon the underlying limestone, the limestone grading into calcareous shales at the contact. After their deposition, they were penetrated by a series of basic igneous rocks, largely in the form of sheets and sills. Then a period of great orogenic movements set in which brought about intense folding in the whole area. The original sediments had been buried to a sufficient depth to come into the comparatively shallow zone of anamorphism for shales. A large series of granitic intrusions accompanied the folding. The granites are huge batholiths which have only been exposed by later erosion at the surface in a few places in this area. Radiating from the batholiths are numerous granitic and pegmatitic dikes. During the earlier stages, the intrusions occurred mainly along the bedding planes which were the lines of weakness, and in many places the rock was so thoroughly injected in this manner that it has become an injected gneiss.

The burial to a considerable depth and the intense stress set up by the orogenic movements which produced the folding, together with the metamorphic effects of the granitic and pegmatitic intrusions, brought about the recrystallization of the constituents of the original shale and associated sediments into mica and related schists. The earlier basic intrusives were also involved in the dynamic metamorphism. The metamorphism appears to be least pronounced north of Croton Village and in those places in the vicinity of Peekskill where the schist did not come under the influence of the local contact metamorphic effects of the Cortlandt series.

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[50] Waldemar Lindgren: "Some modes of deposition of copper ores in basic rocks." Econ. Geol., Vol. VI, pp. 687-694. 1911.

[51] Zeits. f. Kryst. u. Miner., 16 Band, pp. 168-173. 1890.

The granitic and pegmatitic intrusions, especially the latter, continued for some time after the folding had ceased. These later intrusions took the form of dikes. Toward the end of the period of folding, or perhaps after it had ceased altogether, a number of intrusions of basic igneous rocks occurred at several places in the area under discussion. The largest of these constitutes the Cortlandt series Near Peekskill. Some of the igneous rocks were rich in olivine and have been altered to serpentine. Granitic and pegmatitic intrusions were still occurring at the time, as these later basic rocks are cut by granite and pegmatite dikes in several places. A hornblende porphyrite cutting pegmatite near New Canaan, Connecticut, is the latest in age of the intrusives present in the region under discussion.

The age of the Manhattan schist, as already mentioned, is still a disputed question. This will be further discussed after the formations north of the Highlands have been described.

Peekskill Phyllite

As has already been mentioned in a previous chapter, the section across the Peekskill Creek valley northeast of Peekskill contains a series of formations which are quite different from those exposed anywhere else south of the Highlands, with the exception of Tompkins Cove on the west side of the Hudson River, which is merely a continuation of this same belt. The lowest member here resting upon the gneiss is a quartzite about six hundred feet thick. This is followed by a fine-grained crystalline limestone varying in color from blue to white which in turn is succeeded by a dark gray to black phyllite. On account of folding, it is hard to determine the exact thickness of the limestone and phyllite, but the former is probably about one thousand feet, while the thickness of the latter is probably a great deal more. The phyllite is well exposed on the northwest side of the valley which occupies the limestone belt, while the quartzite shows on the southeast side. All the formations dip steeply toward the southeast. Most of the phyllite has a dark bluish gray color and rather fine texture. Pyrite crystals are quite abundant in certain beds.

A thin section of the fine dark bluish gray rock, when examined under the microscope, shows a distinctly foliated structure and is found to consist largely of an aggregate of minute quartz grains and sericite flakes, with abundant iron oxides scattered through the whole mass and also to a certain extent concentrated in distinct bands parallel to the foliation. Occasionally, small stringers of secondary quartz also parallel to the foliation may be noticed.

A chemical analysis made by the writer of the above described specimens gave the following composition:

Analysis of Phyllite

	Per cent
SiO_2	61.04
Al_2O_3	15.87
Fe_2O_3	1.74
FeO	4.32
MgO	3.26
CaO	2.39
Na_2O	1.83
K_2O	3.26
H_2O+	1.82
H_2O-	.09
CO_2	4.24
TiO_2	.91
Total	100.77

A lighter colored coarser-grained type was also examined under the microscope. It consists largely of quartz and sericite, with minor amounts of black iron oxides. A little calcite in isolated crystals is also present. Recrystallization has proceeded much further than in the previous case. The sericite flakes are all oriented parallel to the foliation, while the quartz grains are all more or less elongated parallel to it (Pl. XIV, Fig. 1). An occasional quartz grain reaches a diameter of .5 millimeter, but most of them are much smaller.

All who have studied this section have correlated these formations with the Poughquag-Wappinger-Hudson River series north of the Highlands. Dr. Charles P. Berkey,[52] who has made the most recent and detailed study of this area, has come to the conclusion that these are not, however, the equivalent of the Inwood-Manhattan series south of the Highlands, as others have thought, basing his view upon the relation of the Peekskill Valley formation to a belt of limestone occupying Sprout Brook Valley to the northwest, which he thinks is the equivalent of the Inwood limestone. A further discussion of these two views will be taken up after the formations north of the Highlands have been described.

Poughquag-Wappinger-Hudson River Series

Just north of the Highlands of the Hudson and east of the Hudson River itself, a quartzite to which the name Poughquag has been given

[52] "Structural and Stratigraphic Features of the Basal Gneisses of the Highlands." N. Y. State Mus. Bull. 107, pp. 361-378. 1907.

rests unconformably upon the pre-Cambrian gneisses. This is followed conformably by a limestone known as the Wappinger, which in turn is succeeded by a thick series of shales belonging to the Hudson River group.

POUGHQUAG QUARTZITE

The Poughquag quartzite reaches a maximum thickness of about six hundred feet. It is usually a compact, granular silicified quartz sandstone of medium grain, with occasionally a fine conglomerate at the base and sometimes finer grained quartzitic shales at the top. Its fossil contents show that it is of Lower Cambrian age.[53]

In certain places, as along the Matteawan inliers of pre-Cambrian gneiss, a coarse granitic stratum rests on the upturned gneiss, and this is followed by a somewhat foliated, finer grained quartzitic rock. This granitic stratum has been interpreted by C. E. Gordon[54] as representing decayed portions of the old pre-Cambrian gneisses which were partly reworked by the advancing Cambrian sea and later covered by quartzitic sands.

Usually, wherever the relationship of the quartzite to the gneiss can be made out, the contact is seen to be an unconformity, and it is evident that the foliated structure of the gneisses dates back to a period of folding prior to the deposition of these Lower Cambrian sediments.

Since the deposition of the quartzite, the region has been involved in extensive thrust faulting which has shoved the older pre-Cambrian gneisses upon the later formations. In some cases, the quartzite moved with the gneiss, while in others the gneiss moved over it. The quartzite, although never violently folded, was nevertheless greatly disturbed by orogenic movements in certain places.

WAPPINGER LIMESTONE

Following the Poughquag quartzite just north of the Highlands comes the Wappinger limestone. In this region, it has a thickness of about one thousand feet. Portions of it are magnesian in character. A belt of this limestone runs from the Hudson River in a northeasterly direction along the northwestern margin of the Highlands and then turns northerly up the Clove Valley where it dies out. To the east of the Clove Valley, it passes underneath a thick series of phyllites and schists, appearing again farther east in the Dover-Pawling Valley.

C. E. Gordon[55] has identified fossils of Lower Cambrian, Beekmantown

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[53] J. D. DANA: Am. Jour. Sci., 3rd ser., Vol. 3, pp. 250-256. 1872.

[54] "Geology of the Poughkeepsie Quadrangle." N. Y. State Mus. Bull. 148, p. 46. 1911.

[55] *Ibid.*, p. 71.

and Trenton ages from this belt, showing that all these terranes are present. He called attention to the fact that as one goes eastward in this belt the rock displays greater crystallinity. Much evidence of crushing becomes manifest and bunches and veinlets of calcite, nests of quartz and stringers are abundant, indicating hydrothermal activity. These changes have obliterated all traces of organic remains.

The limestone of the Clove Valley is essentially a fine-grained gray to white crystalline variety. The individual calcite grains range in size from one-tenth to two-tenths millimeter in diameter. Small bunches and stringers of secondary quartz are frequently present. On the east and west, the limestone is overlain by phyllites belonging to the Hudson River series.

The limestone appears again six miles to the east in the Dover-Pawling Valley. Here it is considerably more metamorphosed, as is shown by its coarse crystalline texture. In places, as in the vicinity of South Dover and Wingdale, it is quite pure and makes an excellent marble. It has been quite extensively quarried at these places. At other localities, phlogopite and tremolite occur quite abundantly distributed through it. The development of tremolite crystals in the limestone is especially well shown in some of the cuts along the New England Railroad from Towners to West Patterson. They frequently become an inch long and over a quarter of an inch in diameter and make up a goodly percentage of the rock.

HUDSON RIVER SLATES, PHYLLITES AND SCHISTS

Resting on the Wappinger Limestone is a thick series of slates belonging to the Hudson River group. The slates range in age from Trenton into Cincinnatian.[56] These strata are strongly folded and crumpled, and for this reason their exact thickness is unknown, but probably exceeds several thousand feet.

Just east of the Hudson River, a slaty shale derived from an impure argillaceous mud is the predominating type. Interbedded with this shale are occasional sandstone beds. Following these slates eastward from the Hudson River, an increase in the amount of metamorphism which they have undergone becomes very noticeable. In the vicinity of Arthursburg, they have been altered to slaty phyllites and graywackes.

The formation at Arthursburg is typically a slaty phyllite broken up into a large number of comparatively thin lamellæ by numerous parallel cleavage planes. It has a dark bluish gray color and is fine grained. In thin section under the microscope, it is seen to be made up chiefly of a

[56] C. E. Gordon: N. Y. State Mus. Bull. 148, p. 96. 1911.

fine aggregate of quartz and sericite. The quartz occurs in minute grains usually more or less elongated parallel to the cleavage. The little sericite scales occur interspersed among the quartz with their basal section in the plane of cleavage. Considerable amounts of iron oxide occur scattered throughout the mass. A little biotite in minute scales has also commenced to develop. Bands with sericite predominating over the quartz alternate with bands in which the quartz predominate.

Going eastward, the rock begins to take on more and more the nature of a true phyllite. A thin section from a specimen obtained three miles east of Arthursburg has the grains of quartz and flakes of muscovite somewhat coarser than that at Arthursburg. Considerable chlorite also appears in this particular specimen. Oxides of iron are plentiful, often concentrated along more or less parallel bands. Magnetite occurs in grains up to five-tenths millimeter in diameter. In crystallizing, it has forced the other mineral aside, and the flakes of sericite now curve around it. The structure is distinctly foliated.

Four miles east of Arthursburg is a belt of Wappinger limestone, the more ready erosion of which accounts for the Clove Valley. On the east side of the valley, the phyllites are again found overlying the limestone. The rock has a rather fine texture, with numerous easily recognizable flakes of biotite scattered through it. Pyrite also is abundant. Under the microscope, the fine-grained mass is seen to consist of an aggregate of sericite and quartz, associated with which are large quantities of iron oxide in very fine particles. In the finer matrix occur numerous larger and more prominent flakes of biotite with their basal sections in the plane of foliation (Pl. XIV, Fig. 2). They all show a more or less ragged outline. Pyrite is present in considerable quantities. The fine-grained matrix in this case is a good deal more coarsely crystalline than that found west of the Clove Valley.

A short distance east of the above contact, the biotite becomes a very prominent feature. Occasional crystals of garnet also appear. Under the microscope, it is seen that the fine-grained mass of sericite, chlorite and quartz with some iron oxide is a little coarser than in the previous cases. This shows a distinct foliated structure. On the other hand, the biotite is not oriented parallel to the foliation but occurs in rather prominent flakes at all angles to it. A few isolated grains of garnet appear for the first time.

About one-half mile east of the above locality, the phyllite begins to grade into a fine-grained schist. The sericite or muscovite becomes quite abundant and gives the rock a satiny luster. Garnet becomes very prominent. Its crystals average about one-tenth inch in diameter and show good crystal outline. In thin section under the microscope, the rock shows a distinctly foliated structure and is seen to be made up of an aggregate of sericite and quartz. In it are large crystals of garnet, biotite and staurolite. The latter mineral makes its first appearance but is not as yet very abundant.

A specimen collected two and one-half miles east of the above locality shows abundant biotite and an occasional garnet crystal embedded in a fine-grained matrix. This matrix resolves itself under the microscope into an aggregate of quartz and sericite, with abundant iron oxide scattered through it. A little plagioclase and a few small tourmalines are also present. The rock shows a distinctly foliated structure (Pl. XIV, Fig. 3). It is evident that the metamorphic changes here have not reached quite so advanced a state as in the case above. Most but not all of the biotite crystals are oriented parallel to the foliation.

A specimen from an outcrop occurring three and one-half miles east of the Clove Valley showed a medium fine texture and distinctly foliated structure. Abundant garnet and biotite show in the hand specimen. Under the microscope, the main mass of the rock is seen to consist largely of quartz and sericite. The biotite is full of quartz inclusions.

A specimen collected a short distance east of the above locality shows a marked schistose structure. It has a silky luster due to the presence of numerous fine sericite flakes. Garnet and biotite are prominently developed. In thin section, the sericite flakes all show more or less parallel alignment to the foliation. Quartz occurs in small grains interspersed between the sericite. Biotite is present in considerable amounts in fairly large flakes embedded in this matrix. The same is true of garnet. An occasional staurolite crystal has also been developed. Some chlorite is present. The texture in this specimen is a good deal coarser than any described thus far.

A half mile east of this locality near the western contact of the Dover-Pawling limestone with the schists the rock is quite coarsely crystalline. Garnet, biotite and abundant staurolite crystals can be readily made out embedded in a fine matrix which has a silky luster due to the abundant presence of muscovite. The rock is a typical staurolite-mica schist. In thin section, the matrix is seen to be made up of medium-grained aggregate of muscovite and quartz, with an occasional grain of orthoclase and plagioclase (Pl. XIV, Fig. 4). The quartz occurs in fairly large grains at times. The flakes of muscovite are oriented parallel to the foliation. Biotite is also abundant and occurs in larger flakes than the muscovite also oriented parallel to the foliation. Staurolite and garnet with good crystalline outlines occur abundantly interspersed in this matrix. They are full of quartz inclusions. A little chlorite derived from altered biotite is also present.

After crossing the Dover-Pawling Valley, the schists are again exposed overlying the limestone on the east side of the valley. A specimen collected from the west slope of Purgatory Hill east of Pawling, when examined under the microscope, shows a medium coarse texture and distinctly foliated structure, due chiefly to the parallel orientation of the biotite (Pl. XIV, Fig. 5). The mineral composition is principally biotite, plagioclase, orthoclase and quartz. The plagioclase is present in large amount. It has a maximum extinction angle of 25°, measured in sections at right angles to the albite lamellæ, which would indicate an andesine or acid labradorite variety. A few small garnet grains and some magnetite are also present. The garnet is remarkably free from inclusions.

Another section examined from a specimen collected three and one-half miles east of Pawling shows a coarse-grained crystalline texture and schistose structure. It is composed mostly of biotite, feldspar, quartz and garnet. The biotite shows marked pleochroism from light yellowish brown to deep brown. Only minor amounts of muscovite are present. The feldspar consists mostly of plagioclase with some orthoclase. Considerable quartz is also present. A few small grains of staurolite and a single crytal of tourmaline were also noted in the section examined.

Going south along the contact of the Dover-Pawling limestone with the overlying schist, the schist does not vary a great deal in composition. In places, quartz becomes more prominent and the amount of feldspar increases.

On the north side of the valley at Haviland Hollow, east of Towners, a dense, dark, finely granitoid rock occurs apparently interbedded with the mica schists. It is being quarried for road metal. On examination in thin section under the microscope, the rock is seen to have a granitoid texture and to consist chiefly of the quartz, plagioclase and hornblende. The plagioclase gives extinction angles up to 32° 30′ in sections at right angles to the albite lamellæ. Some sections do not show the twinning but show good cleavage. They are biaxial and optically positive. The plagioclase is evidently labradorite. The hornblende shows marked pleochroism from brownish yellow through deep yellowish brown to dark green. A little biotite is present. Titanite occurs in considerable amount as accessory mineral. Magnetite and apatite are other accessory constituents which are present. The rock shows a cataclastic structure, and much of the quartz is undoubtedly of secondary origin. The mineral composition indicates an igneous rock of the composition of a quartz diorite. From the amount of dynamic metamorphism that it has undergone, it was evidently intruded into the shales now represented by the mica schist prior to the period of folding as an intrusive sheet.

Pegmatite sheets and dikes become quite abundant in the mica schists east of the Dover-Pawling Valley. These are usually present in the form of intrusive sheets and lenses, parallel to the foliation of the schists which in most cases also represents the bedding planes of this formation. Dikes also occur. West of the Dover-Pawling Valley, the pegmatites are not very prominent, occurring only occasionally in the schists just west of this valley. The tourmaline noticed in one of the sections of phyllite collected west of the Dover-Pawling Valley was probably derived from emanations given off by these pegmatitic intrusions.

HISTORICAL GEOLOGY

As seen from the above description of the formations north of the Highlands, a sandstone was laid down unconformably upon the upturned edges of the folded pre-Cambrian gneisses during lower Cambrian time. Then followed a period of limestone deposition which continued into Trenton time. Sedimentation was not continuous during this entire interval, but there were several retreats of the sea followed by re-advances, so that there are a number of breaks in the limestone represented by disconformities. These can only be recognized on paleontological evidence. The limestone deposition was followed by that of a thick series of dark shales which range in age from Trenton to Cincinnatian.

Then at the close of the Ordovician, there was inaugurated a period of great orogenic movement, commonly known as the Green Mountain uplift. The formations described were thrown into a series of anticlines and synclines whose axes have a northeast and southwest trend. Accompanying this folding, there occurred the intrusion of a large number of pegmatitic sheets and lenses in the eastern portion of the area, which are undoubtedly closely related to the granitic batholiths occurring still farther East in Connecticut. The quartz diorite described from Haviland Hollow, as already mentioned, was intruded prior to the folding.

The burial of these formations to a depth sufficient to bring them into the zone of anamorphism of Van Hise and the intense pressure accompanying the great orogenic movement which produced the folding together with the injection of a large amount of pegmatitic material had a marked metamorphic effect upon the formation involved, causing the limestone in the eastern portion of the area to become completely recrystallized and bringing about the formation of numerous lime and other silicates in it while the overlying shale was converted into a mica schist.

Going west from the Dover-Pawling Valley, the metamorphic effects become less and less noticeable, until in the vicinity of the Hudson River fossil remains can still be readily identified in the limestone, and the shale has hardly been converted into a slate. The transition from a garnetiferous staurolitic mica schist to a phyllite takes place within a distance of four and one-half miles in passing from the western margin of the Dover-Pawling Valley to the eastern side of the Clove Valley.

Such a change in so short a distance can hardly be explained on the basis of regional metamorphism alone. The axis of most severe orogenic disturbance runs in a northeast-southwest direction through western Connecticut and Massachusetts into Vermont. Here the pressure was greatest, as the folding and crumpling are much more pronounced than they are farther west where the beds become less disturbed. Along this line of most severe disturbance a series of granitic intrusions occurred at the time of the folding. These sent out radiating pegmatitic dikes and sheets into the adjacent formations which must have had a marked metamorphic effect upon them and have brought about the recrystallization of the constituents of the shale into mica schist as already pointed out in the case of the Manhattan schist.

Professor Van Hise[57] has described a very similar occurrence from the Black Hills of South Dakota where a great intrusive batholith of granite is surrounded by sedimentary rocks which are cut by a series of radiating pegmatitic dikes extending out from the central core. Remote from the intrusive, the sedimentary rocks are slates, while adjacent to them they are schists and gneisses.

From the study of the transition of slates to schists north of the Highlands, the following seems to be the order in which the different metamorphic minerals were developed. Sericite was the first new mineral to form and was accompanied by a partial recrystallization of the quartz present. The formation of chlorite may have occurred at the same time. Next biotite began to develop, the iron present in the form of oxide entering into its composition. Biotite was followed by garnet. Still later staurolite made its appearance. The sericite by this time had recrystallized into true muscovite. Feldspar also began to develop at this stage. As these changes were going on, the texture of the rock was growing progressively coarser. In the final stages, large quantities of feldspar appeared, while the muscovite became less abundant, the former developing at the expense of the latter. In some of these gneissic phases, the muscovite disappeared entirely. Staurolite also dropped out except for an occasional grain. The garnet become quite free from inclusions during these later recrystallizations.

[57] U. S. Geol. Surv. Mon. XLVII, p. 724. 1904.

Faulting has occurred in the region since the period of folding. In places along the northern borders of the Highlands, the pre-Cambrian gneisses have been thrust upon the paleozoic strata. This faulting probably accompanied the crustal movements which involved eastern North America at the close of the Paleozoic.

Comparison of Inwood-Manhattan and Poughquag-Wappinger-Hudson River Series

As has already been shown, there is still a marked difference of opinion as to the relationship of the Inwood-Manhattan series south of the Highlands to the Poughquag-Wappinger-Hudson River series to the north. One view is that they are equivalents, while the other is that the Inwood-Manhattan series consists of much older formations belonging to the pre-Cambrian. The arguments in favor of their being the same in age will be taken up first, and then those against such a correlation will be considered.

Probably the strongest argument in favor of the correlation of the two series is the fact that they represent almost the same lithological succession of formations, the only difference being that the one is more metamorphosed than the other. South of the Highlands, a quartzite is occasionally found overlying the gneiss, on top of which rests the Inwood limestone, followed by the Manhattan schist. Naturally, this quartzite has been correlated with the Poughquag quartzite north of the Highlands; the Inwood limestone has been regarded as the equivalent of the Wappinger, and the Manhattan schist has been considered the representative of the Hudson River slates by many geologists. The upper two formations in each case correspond quite closely in thickness, but the Poughquag quartzite on the other hand is usually much thicker than the Lowerre quartzite south of the Highlands, even where this is developed to its greatest extent.

From the descriptions of the Hudson River shale and slate and the Manhattan schist already given, it has been shown that the latter was derived from a sediment very similar in composition to that of the former, and where it has been sufficiently metamorphosed, as in the eastern portion of Dutchess County, it has been converted into a mica feldspar schist practically identical with the Manhattan schist. Likewise, the Wappinger limestone of the Dover-Pawling Valley in eastern Dutchess County also shows the same coarse crystalline texture that the Inwood limestone possesses and has tremolite and phlogopite developed in it to an equal extent.

A quartz diorite was found occurring at one place in the schist north of the Highlands which had practically the same relationship to the latter that the hornblende schist has to the Manhattan schist south of the Highlands.

The folding of the formations north of the Highlands was also accompanied in eastern Dutchess County and western Connecticut, where the folding was severest, by the intrusion of granites and pegmatites similar to those south of the Highlands. Those who hold that the two series are equivalent believe that the orogenic movements which brought about the folding and metamorphism south of the Highlands were also part of the Green Mountain uplift which occurred toward the close of Ordovician time and brought about the metamorphism north of the Highlands. The axes of the folds in the two regions run in the same general direction.

The occurrence of an area of phyllite south of the Highlands northeast of Peekskill has been cited as evidence in favor of the Ordovician age of the Manhattan schist, being regarded by those who hold to the Ordovician age of the schist as a less metamorphosed phase of this formation which is very similar to the Hudson River slates and phyllites north of the Highlands. This phyllite has been regarded by all who have studied it as of Ordovician age.

There is an interval of a little over one and a half miles between the nearest outcrops of phyllite and schist. As has already been remarked, where the schist southeast of Peekskill is at a sufficient distance from the contact metamorphic effects of the Cortlandt intrusive, it does not show as marked metamorphism as does the typical Manhattan schist farther south and southeast. Feldspar is almost entirely absent, and sericite is an abundant constituent of the rock. The schists north of Croton Village also are not as metamorphosed as the typical Manhattan schist of southeastern New York. Some of the garnetiferous staurolite mica schist very similar to that described from north of the Highlands is also present here. Clearly transition phases between phyllites and typical mica feldspar schist similar to those north of the Highlands are present in the area south of Peekskill and north of Croton Village, but in most cases they have been obscured by the contact metamorphism accompanying the intrusion of the Cortlandt series. As seen from the description of the schist north of the Highlands, the transition from phyllite to schist may take place within a comparatively short distance. It is reasonable to believe, therefore, that the Peekskill phyllite may represent a less metamorphosed phase of the Manhattan schist.

Of those who have made a careful study of the Manhattan schist, Dr. Charles P. Berkey[58] has given the best arguments against the correlation

[58] N. Y. State Mus. Bull. 107, pp. 361-378. 1907.

of this formation with the Hudson River series He bases his conclusions upon a number of facts.

One is the relation of the Peekskill Valley quartzite, limestone and phyllite to the crystalline limestone in the Sprout Brook valley. Dr. Berkey considers the former to represent a down-faulted block of the Poughquag-Wappinger-Hudson River strata, as already mentioned, while the latter, he thinks, is the equivalent of the Inwood, on account of its thickness and lithological resemblance to that limestnoe, and that it is not one of the interbedded limestones occurring in the pre-Cambrian Highland gneisses farther north. In the Peekskill Valley, there are five hundred feet of quartzite corresponding to the Poughquag quartzite, while in the Sprout Brook valley the limestone apparently rests upon the gneiss. This limestone, moreover, is very much more metamorphosed than that occurring in the Peekskill Valley. All these facts go to show that they cannot be correlated, and that if the former is the Inwood, the latter must be later in age.

Another strong argument against such a correlation is that a quartzite rarely appears between the Inwood limestone and the underlying Fordham gneiss, and where it does occur it is quite thin and can be followed for only a short distance. Where it is present, it appears to be a part of the gneiss, as it is conformable with it and apparently grades into it. At other places, the Inwood limestone rests conformably upon the Fordham gneiss. North of the Highlands, on the other hand, the Poughquag quartzite is usually well developed and reaches a thickness of six hundred feet in places. It rests unconformably upon the pre-Cambrian gneisses which Dr. Berkey[59] believes are the equivalent of the Fordham gneiss. If the two series of formations are equivalent, it is hard to understand why there should be such a marked unconformity north of the Highlands, while to the south they are apparently conformable. Evidently such a correlation is impossible if the Highland gneisses are of the same age as the Fordham gneiss of southeastern New York. In this connection, however, it is interesting to note that in most of the places where the contact between the pre-Cambrian gneisses and Cambrian quartzites, schists and conglomerates is exposed in northwestern Massachusetts and western Vermont, the two formations are in apparent conformity.[60] There are other localities in this same region where they are unconformable. The work of Pumpelly, Wolff and Dale in the Green Mountains of Massachusetts showed that this conformity was only an apparent one and that the for-

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[59] *Op. cit.*, p. 361.

[60] T. NELSON DALE: Structural details in the Green Mountain region and in eastern New York. U. S. Geol. Surv. Bull. 195, p. 18. 1902.

mations were not actually continuous. At one place, two dikes of basic eruptive rock were found cutting the gneiss but not the overlying quartzite. The eruptive rock had weathered more readily than the gneiss and depressions were formed which were later filled with pebbles and sand by the advancing Cambrian sea.[61] This proved that the gneisses were of pre-Cambrian age, while the quartzite and conglomerate were known to be of Cambrian age from fossils found elsewhere in the neighboring regions. The apparent conformity evidently was only a structural one due to the general lamination forced upon the rock by the folding.

In the case of the Fordham gneiss, however, parts of which at least are of sedimentary origin, as shown by the occurrences of interbedded limestone in it, the foliation appears to be parallel to the bedding planes, as the bands of interbedded limestone are always parallel to the foliation of the gneiss.

The fact that the phyllite and schist occur so close together in the vicinity of Peekskill, which has been cited as strong evidence in favor of the later origin of the former, is not as strong an argument as one might at first think when we consider that this change does take place within a not very much greater distance north of the Highlands and also that the intrusion of the Cortland series must have had considerable effect in obliterating transition phases if they did occur. As has already been mentioned, there are still evidences present of what appear to be such transition phases.

From the above discussion, it is seen that there is still doubt as to the true age of the Manhattan schist. A much more detailed study of the geology of southeastern New York State and western Connecticut and Massachusetts than has yet been attempted will have to be made before a definite conclusion can be arrived at.

Acknowledgments. The writer is greatly indebted to Professor James F. Kemp, at whose suggestion this study of the Manhattan schist was undertaken, and to Professor Charles P. Berkey for many helpful suggestions as the work progressed. The work was carried on in the laboratories of the Department of Geology of Columbia University.

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[61] U. S. Geol. Surv. Mon. XXIII, p. 11. 1894.

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VITA

Charles Reinhard Fettke: Born March 25, 1888, in San Francisco, California. Received a grammar and high school education at Tacoma, Washington. Attended Washington State College at Pullman, Washington, during the year 1906-07 and the University of Washington at Seattle from 1907 to 1910, receiving the degree of Bachelor of Science in Mining Engineering from the latter institution in 1910. Graduate student at Columbia University from 1910 to 1913, receiving the degree of Master of Arts in 1911.

Field assistant, Washington Geological Survey, during the summers of 1909, 1910 and 1911. Assistant in geology at Columbia University from 1911 to 1913. Instructor in geology during Summer Session of 1912. Geologic Aid, United States Geological Survey, during summer of 1913. Instructor in geology, Carnegie Institute of Technology, Pittsburgh, Pa., 1913.

Member of Sigma XI and American Association for the Advancement of Science. Associate member of New York Academy of Sciences.

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PLATE VIII

HORNBLENDE SCHIST AND EPIDOSITE

FIG. 1. Hornblende schist sheet in Manhattan schist.
Near W. 160th Street and Edgecomb Avenue, New York City.

FIG. 2. Epidosite in hornblende schist.
The two middle bands between the light bands are epidosite.
South shore, Croton Lake, New York.

1

2

PLATE IX

PEGMATITE DIKES

FIG. 1. Pegmatite dike in Inwood limestone.
West 204th Street, east of Sherman Avenue, New York City.

FIG. 2. Banded pegmatite dike in Manhattan schist.
Speedway at Ft. George, New York City.

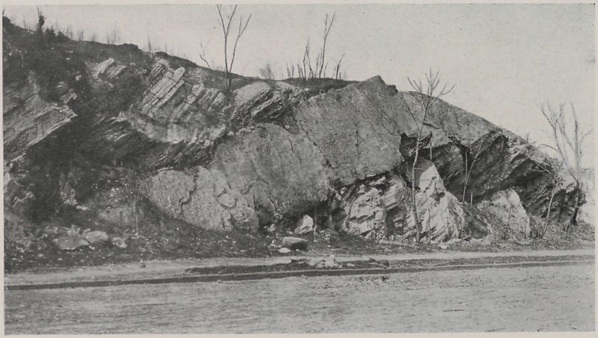

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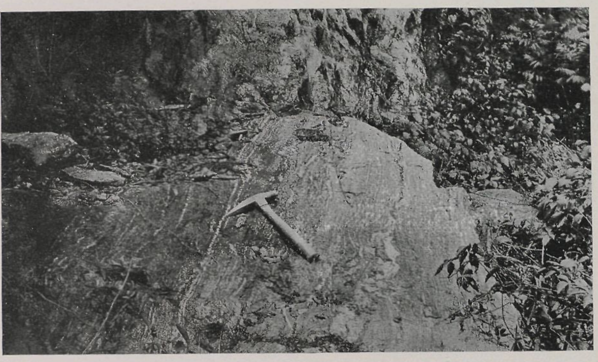
PLATE X

MANHATTAN SCHIST AND AUGEN GNEISS

FIG. 1. Manhattan schist injected with pegmatite.
Near Rye, Westchester County, New York.

FIG. 2. "Augen" gneiss.
South of Bedford Village, Westchester, New York.



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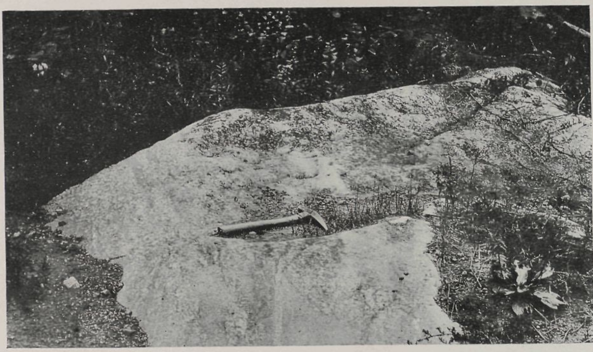

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PLATE XI

SPECIMENS OF AUGEN GNEISS

FIG. 1. "Augen" gneiss.
South of Bedford Village, Westchester County, New York.

FIG. 2. "Augen" gneiss.
South of Bedford Village, Westchester County, New York.

1

2

PLATE XII

PHOTOMICROGRAPHS OF GNEISS, SCHIST AND GRANODIORITE

FIG. 1. Interbedded gneiss.
Catskill Aqueduct tunnel underneath Harlem River at High Bridge, New York City.
Magnified 22.5 diameters. Crossed nicols.

FIG. 2. Fordham gneiss.
East of High Bridge, New York City.
Magnified 22.5 diameters. Crossed nicols.

FIG. 3. Cyanite schist.
West 120th Street, east of Amsterdam Avenue, New York City.
Magnified 22.5 diameters. Crossed nicols.

FIG. 4. Hornblende schist.
South shore, Croton Lake, New York.
Magnified 22.5 diameters.

FIG. 5. Harrison granodiorite.
Greenwich, Connecticut.
Magnified 22.5 diameters.

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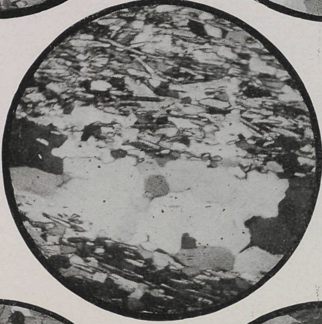

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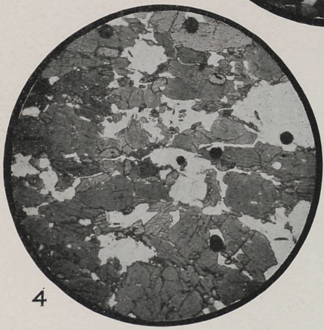

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PLATE XIII

PHOTOMICROGRAPHS OF SCHIST

FIG. 1. Mica-feldspar-quartz schist.
Southeast corner West 116th Street and Broadway, New York City.
Magnified 22.5 diameters.

FIG. 2. Gray gneissoid variety of schist.
West 42nd Street, near 5th Avenue, New York City.
Magnified 22.5 diameters. Crossed nicols.

FIG. 3. Mica schist.
Verplanck, Westchester County, New York.
Magnified 22.5 diameters. Crossed nicols.

FIG. 4. Mica schist.
North of Croton-on-the-Hudson, Westchester County, New York.
Magnified 22.5 diameters.

FIG. 5. Staurolite mica schist.
North of Croton-on-the-Hudson, Westchester County, New York.
Magnified 22.5 diameters.

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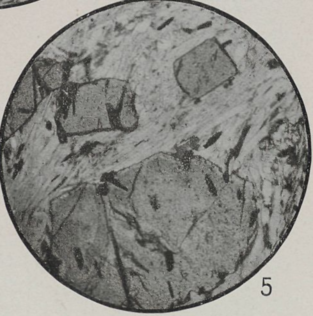

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PLATE XIV

PHOTOMICROGRAPHS OF PHYLLITE AND SCHIST

FIG. 1. Phyllite.
East of Peekskill Creek Valley, New York.
Magnified 22.5 diameters. Crossed nicols.

FIG. 2. Phyllite.
East of Clove Valley, Dutchess County, New York.
Magnified 22.5 diameters. Crossed nicols.

FIG. 3. Mica schist.
West of Wingdale, Dutchess County, New York.
Magnified 22.5 diameters.

FIG. 4. Staurolite mica schist.
West of Wingdale, Dutchess County, New York.
Magnified 22.5 diameters. Crossed nicols.

FIG. 5. Mica-feldspar-quartz schist.
East of Pawling, Dutchess County, New York.
Magnified 22.5 diameters. Crossed nicols.

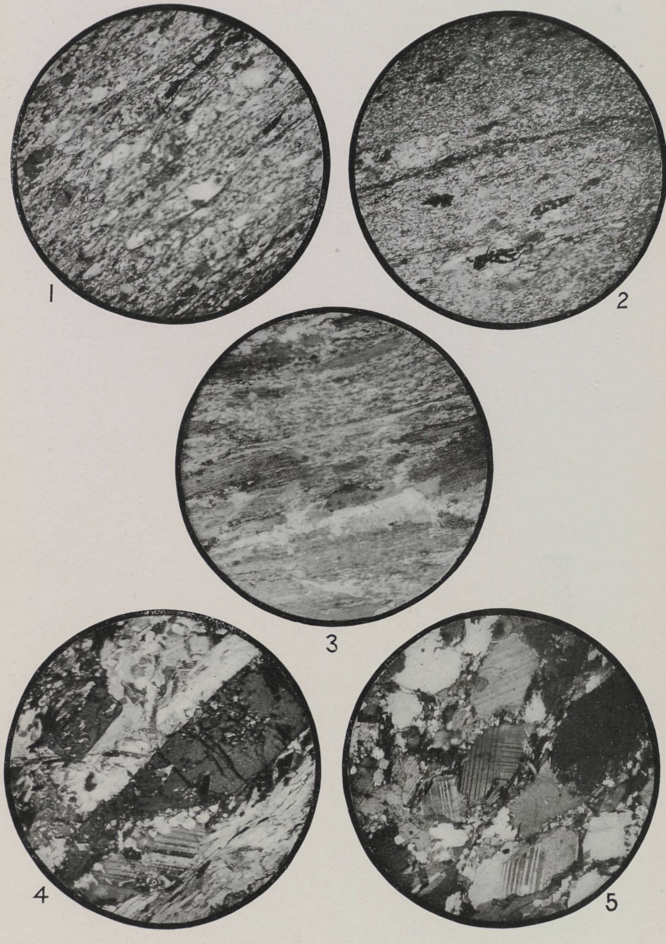
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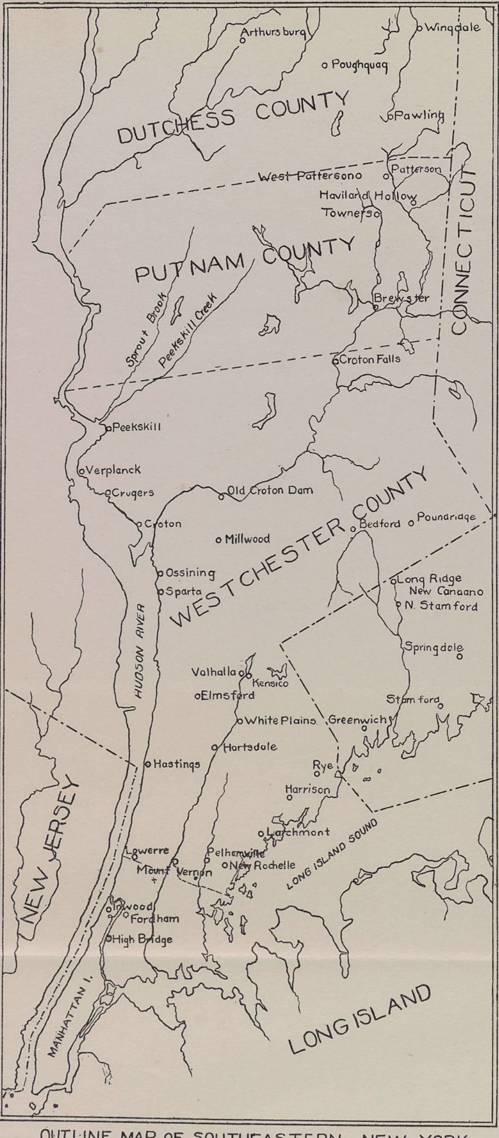
PLATE XV

OUTLINE MAP OF SOUTHEASTERN NEW YORK



OUTLINE MAP OF SOUTHEASTERN NEW YORK.