GEOLOGY AND ORIGIN OF THE KAOLIN
AT EAST MONKTON, VERMONT

By

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ABSTRACT

Extensive deposits of kaolin exist in west-central Vermont, near the village of East Monkton, in the south-central part of the town of Monkton. These deposits are of considerable geological interest as well as of importance to the economy of the State of Vermont.

Kaolin commonly occurs in such relationships as to indicate that it has been formed as a product of surface weathering. Throughout the State of Vermont, products resulting from such alteration have been, for the most part, removed by the erosive action of the continental glacier.

The kaolin deposits at East Monkton are peculiar in that they do not occur in association with highly feldspathic rocks. The kaolin-bearing horizons occur within the Cheshire Quartzite of Lower Cambrian age. The formation consists of layers of relatively pure quartzite interbedded with a black phyllitic rock, best described as a graphitic, quartz sericite schist.

The zones of fracture and faulting in which the kaolin deposits occur lie between the Mount Holly Complex and the Barber Hill syenitic stock in Charlotte. It is probable that the zone of kaolinization is related to the Mount Holly Complex and bodies of syenite or granite at depth, and that thermal solutions ascending along fault planes and joints have obtained the necessary constituents to react with members of the Cheshire Quartzite to produce the kaolin. Evidence presented in this report indicates that hydrothermal solutions have replaced a great deal of the secondary silica cement in certain quartzite layers with kaolin, and have also altered the phyllitic layers intercalated with the quartzite to kaolin.

INTRODUCTION

Location

The East Monkton area described in this report lies in the west-central part of Vermont in the town of Monkton (Fig. 1). The town of Monkton is located in the Middlebury Quadrangle of the United States Geological Survey, and the specific area of study is situated between latitudes 44°10′ and 44°15′ and longitudes 73°05′ and 73°10′.

The village of East Monkton is located on a paved road approximately midway between the villages of Bristol and Monkton Ridge. Access to the kaolin deposit and the operations of the Vermont Kaolin Corporation is by a dirt road from its junction with the paved road in East Monkton. This road heads west for half a mile and then bears south for a mile to the site of the Vermont Kaolin Corporation (Fig. 2).

Previous Work

One of the reasons for undertaking this study is because very little previous work had been done to explain the origin of the kaolin at East Monkton.

In the first report of the Vermont State Geologist, C. B. Adams (1848) describes the kaolin deposit as "the putty bed" of Mr. Safford Tracy. The report describes the bed as resulting from the decomposition of "graphic granite," which was said to have been observed in various stages of disintegration from the solid rock to kaolin. Mr. Adams regrets that he was unable to verify the statement since the excavation had since fallen in, and upon visiting Mr. Tracy personally he was found to be absent.

Edward Hitchcock (1861, p. 804) contributed very little in the way of a scientific explanation when he flatly stated that "in these beds are the strongest evidences presented of any found in the state, of their production from the decomposition or disintegration of feldspar, as intercalated masses of partially decomposed feldspar are quite abundant in them." Very little, if any, megascopic evidence of "partially decomposed feldspar" within the quartzite formation has been reported or verified since.

William O. Crosby (1890, p. 235) mentions the kaolin at East Monkton by stating that kaolins in Brandon, Monkton and other Vermont towns are covered by drift accumulations and certainly date from pre-glacial times. He then becomes more daring and goes on to say that they are "closely associated not only with limestone, but also with extensive beds of limonite; and since the iron ore has undoubtedly originated in pyritiferous schists which often accompany the crystalline limestones of western New England, free sulphuric acid necessarily results from the oxidation of pyrite and becomes a powerful ally of the meteoric waters in the kaolinization of the schists."

The next attempt at an explanation of the kaolin was presented by E. C. Jacobs in a report of the Vermont

East Monkton

BM 661

Monkton
Ch.

East Monkton
Cem

Smith
Cem

945

WESTERN (UPPER)

EASTERN (LOWER) - HATCH

Clayoit

Pit

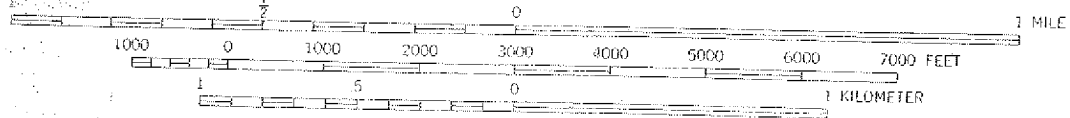VERMONT KAOLIN CORP. PLANT

EASTERN (LOWER) - BUSHEY

Gravl
Pit

x 885

755

Radio
Tower

945

SCALE 1:24000

CONTOUR INTERVAL 20 FEET
DATUM IS MEAN SEA LEVEL

Figure 1. Index map of the area.

Varney
Cem

WESTERN (UPPER)

EASTERN (LOWER) - HATCH

EASTERN (LOWER) - BUSHEY

Figure 2.   Exact location of the kaolin deposit and its approximate extent to date. 5–9–62 VT-62-H
15–2 10   1″ = 500′ approx.

State Geologist (1926). This explanation is very brief indeed and contains about as much scientific reasoning as the previous theories. Jacobs (1926, p. 210) states that "the clay of the Monkton district lies under a quartzite capping, contains fragments of feldspar, and is probably residual."

F. A. Burt (1927) presented a complete report on the origin of the kaolin in Bennington, Vermont; however, in a brief discussion of the Monkton kaolin reported at a later date (Burt, 1930), he revived one of the theories presented back in the 1800's. He discusses the location of three "quarries" in Monkton town, two of them in the north and the central parts of the town, with the kaolin attributed to the decomposition of "graphic granites" underlying the quartzites. Mention is made, though, that the lack of basal exposures of the kaolin, or the records of drillings, prevent the proof or disproof of this theory. A third kaolin deposit is described as lying on the west side of the north-south hill road about one mile south of the village of East Monkton, the site of the operations of the Vermont Kaolin Corporation. Burt's only description of this deposit is that it has thin, alternating beds of white, sugary quartzite, kaolin and sand with the beds having a northeast dip of 35°.

Any further discussions of the origin of the kaolin at East Monkton have resulted only in a restatement of the previously presented theories. These theories depend essentially upon the residual weathering of "graphic granite" or the residual weathering of feldspathic quartzite. Very little evidence has been presented to prove or disprove these theories.

W. M. Cady completed a detailed field study and mapping of the Monkton area, resulting in a report (1945) on the stratigraphy and structure of west-central Vermont.

Nature of the Present Study

Field investigations on which this report is based were carried out during the summer of 1959 and into the spring of 1960.

The kaolin was assumed to be a residual product of the weathering of feldspathic material. This hypothesis may possess some truth, yet no concrete evidence has been presented either for or against it. For this reason the writer has undertaken a detailed field and laboratory study of the deposit, including the structure in which it occurs. This study has led to a hypothesis of its origin not previously proposed for the deposit.

The area in question has been studied from the air in an attempt to gain an overall picture of the regional topography and underlying structure. The outcrops of the structures in the area were not only studied in the field but also in the laboratory by the petrographic examination of rock thin sections.

An important part of the study has been the in-

vestigation of borings taken by the Vermont Kaolin Corporation, and a study of undisturbed material uncovered by excavations. Only by a careful structural and petrographic examination of the underground relationship between the kaolin and the quartzite in which the kaolin occurs, can any true theory of origin be evolved.

Such an investigation in this area is greatly hindered by the extremely thick glacial cover and the consequent scarcity of exposures. This fact may account for any inconsistencies and resulting errors in the interpretation of the structures. Also, the pre-Cambrian complex does not outcrop in this area, and so, any discussion of these rocks is somewhat superficial.

The writer was further hindered in his studies by the fact that the excavations of the Vermont Kaolin Corporation never progressed to a point where a study could be made of the kaolin at depth sufficient to determine the relationship of the kaolin to deep structures. It is hoped that future excavations and borings to a greater depth will verify the seemingly obvious relationships presented in this report.

REGIONAL GEOLOGY

General Statement

The area of this report is in a region of faulting and folding. The major structural features trend north-south (Fig. 3). According to Cady (1945) the major structural features of the region consist of two synclinoria which lie on a common north-south axis and are separated from each other by a culmination or what Cady calls the Monkton "cross anticline." North of this culmination the Hinesburg synclinorium plunges to the north and south of it the Middlebury synclinorium plunges to the south. The area of the so-called Monkton "cross anticline" contains the kaolin deposits and related structures. Here the folded rock formations exhibit east-west faults normal to the strike of incompetent layers, giving rise to an en echelon set of resistant ridges, called hogbacks.

These rock formations near the southeastern margin of the foreland in west-central Vermont, lie in a folded

Scale $\frac{1}{62500}$

Contour interval 20 feet.
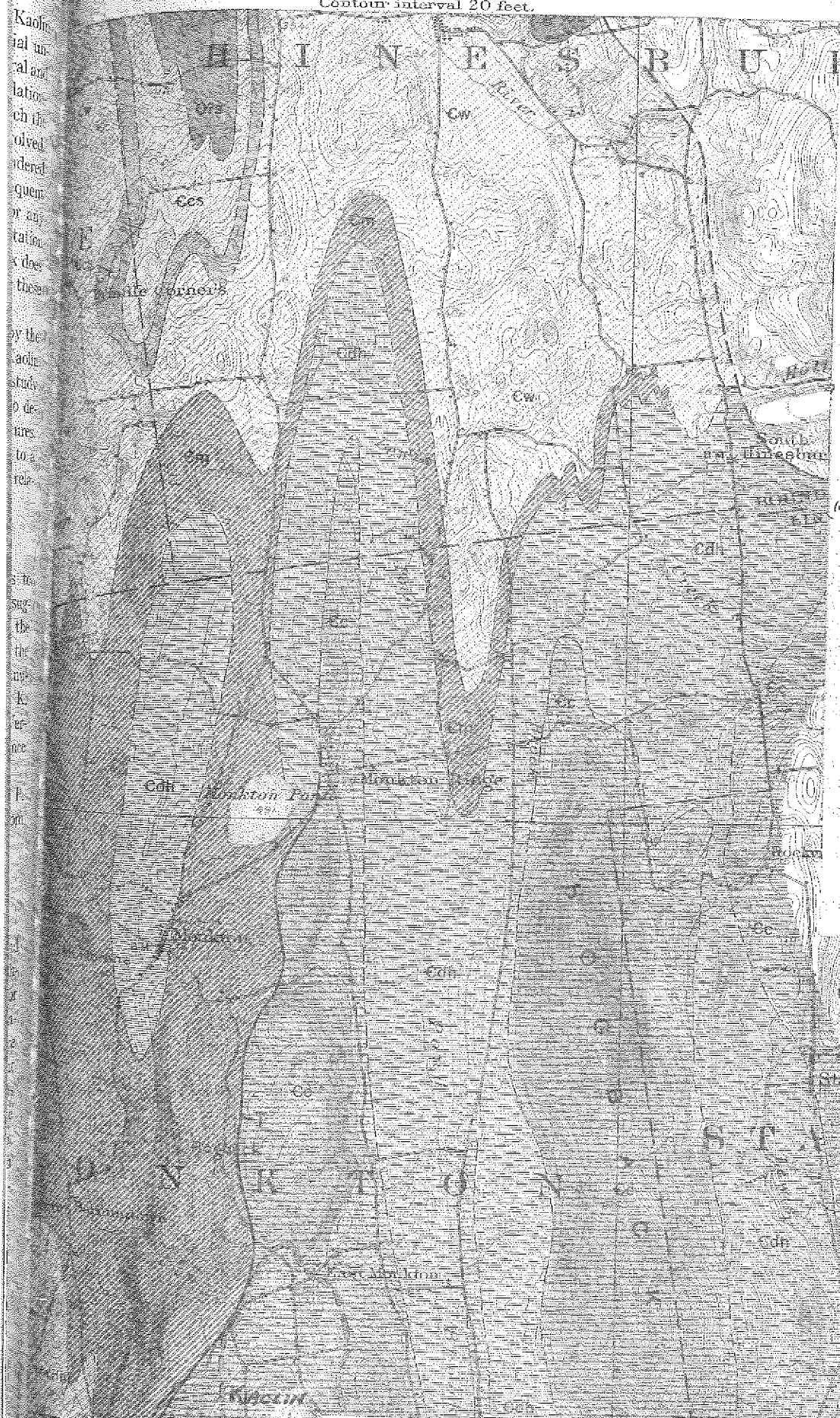
Monkton quartzite
(red quartzite interbedded with pink to gray dolomite)

Parker slate
(dark micaceous shale with flaggy sandstone in lower part)

Dunham dolomite
(buff-weathering siliceous dolomite)

Cheshire quartzite
(pure, massive, white quartzite above less massive brown quartzite)
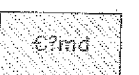
"Mendon series"
(conglomerates, graywackes, dolomites and phyllites)

IGNEOUS ROCKS

Basic dikes

Thrust fault
T., overthrust side

Normal fault
D., downthrown side

Approx. Boundary
of Kaolin-bearing Area

Direction of movement on thrust faults
bordering on klippes and fensters

Geology by Wallace M. Cady
Surveyed in 1934-1941

VERMONT KAOLIN CORP.   Figure 3.   Surface map of formations (Cady, 1945).

belt with a rather persistent north-northeast strike. The formations here are Lower Cambrian in age, with the Cheshire Quartzite as the dominantly exposed rock. The Cheshi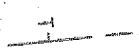re Quartzite has been folded and thrust from the east onto the younger Monkton Quartzite, forming the Monkton fault. In a normal sequence the two quartzites would be separated by the Dunham Dolomite, such as is shown by the exposures to the east in the valleys between the hogback ridges.

STRATIGRAPHY AND LITHOLOGIC DETAIL
TABLE 1
TABLE OF FORMATIONS AT EAST MONKTON

Correlation	Formation	Thickness (feet)
Quarternary	Glacial Deposits	Varying
Post-Ordovician	Intrusives	
Early Cambrian	Monkton Quartzite	0–800 (Cady, 1945)
	Dunham Dolomite	1000–2000 (Cady, 1945)
	Cheshire Quartzite	900–1000 (Cady, 1945)
	Mendon Formation	800–1000 (Cady, 1945)
	Unconformity	
Precambrian	Mount Holly Complex	?

Mount Holly Complex

Although the rocks of the Mount Holly Complex do not outcrop in the East Monkton area, a description of them is important since they are presumed to underlie the region at depth. Any emanations from deep-seated magmatic bodies would pass through rocks of the underlying complex; therefore, the description and mineral composition of these rocks may prove to be pertinent to the theory of kaolin origin proposed in this report.

The closest occurrence of the Mount Holly Complex to the East Monkton area is in the gorge of the Middlebury River at East Middlebury, Vermont. Here the heterogeneous group of rocks is exposed in the core of the Green Mountain anticlinorium, and is probably best described as a complex since the rocks are greatly contorted, recrystallized, and contain no fossil record.

Osberg (1952) describes the rocks in the East Middlebury area as granulites and gneisses of various kinds. Good exposures of quartz-feldspar-biotite granulite outcrop in the Middlebury River about one mile west of the village of Ripton. Feldspar makes up the largest part of the rock, about one third of which is oligoclase with zonally arranged inclusions of epidote and sericite, and the other two-thirds of which is microcline. Tourmaline-bearing pegmatites are commonly intrusive into the granulites, and in some localities the exposures are more than half pegmatite. Outcrops of porphyroblastic microcline-quartz-biotite gneisses are exposed in the river bed at Ripton. These rocks are coarse grained and contain microcline porphyroblasts. Some of these gneisses even take on an augen texture by the clustering of the microcline in pod-shaped areas.

In the Bennington region, Burt (1927) attributes the origin of the kaolin deposits to the residual weathering of this Mount Holly Complex, or what he calls the Woodford gneisses. Burt presents petrographic evidence to the effect that the gneiss is the parent of much of the kaolin. He feels that normal weathering processes are adequate in forming these extensive deposits of kaolin. The Bennington kaolin deposits appear to be related to those at East Monkton since they both occur as parts of the broken chain of a number of such deposits along the base of the Green Mountains. However, the Mount Holly complex does not outcrop at East Monkton as it does in Bennington, and therefore cannot be the weathered parent of the kaolin. Burt makes no mention that the kaolin might be of hydrothermal origin, yet the Mount Holly Complex in this area is intruded by both acid and basic igneous rocks. MacFadyen (1956) describes the Mount Holly Complex at Bennington and finds that the rock is of possible intrusive origin, and is a coarse-grained white gneiss containing quartz, microcline, albite and biotite. He notes that bluish quartz-bearing pegmatites have invaded many of the rocks.

Mendon Formation

There has been no conclusive evidence to indicate that the Mendon Formation outcrops in the area of East Monkton. However, in stratigraphic sequence the Mendon lies immediately below the Cheshire Quartzite, and the point where one ends and the other begins seems to be somewhat indefinite. The upper or western kaolin body which lies in what appears to be a deformed, overturned anticline may possibly be in the Mendon Formation. Even if this body of kaolin does not occur in the Mendon, the Mendon Formation very likely plays an important role in the origin of the kaolin deposits. A hydrothermal theory of the origin of the kaolin would require that emanations and solutions pass through the fractured and faulted zones of the Mendon Formation in order to form the kaolin in the lower member of the Cheshire Quartzite.

Osberg (1952) describes the Moosalamoo Member of the Mendon Formation from its outcrops in the gorge of the Middlebury River at East Middlebury, where it rests with apparent unconformity on the Precambrian Mount Holly Complex. Conglomerate, quartz-muscovite schist, porphyroblastic albite-quartz-biotite-muscovite schist, and quartz-chlorite-muscovite schist predominate in the Mendon Formation. The pebbles making up the conglomerate consist chiefly of quartzite with lesser amounts of vein quartz, pegmatite, gneiss and slate. The matrix is commonly a quartz-chlorite

muscovite schist or a quartz muscovite schist.

In the walls of the Middlebury River gorge, the Moosalamoo can be seen to grade into the overlying Cheshire Quartzite. With an increase in the amount of quartz, the gray muscovite schist becomes a gray muscovite quartzite that in turn grades into a light gray quartzite. It appears that the upper part of the Mendon Formation can easily be included as a member of the Cheshire Quartzite. The Cheshire Quartzite definitely contains argillaceous layers, and the exposures in the gorge at East Middlebury and at East Monkton contain the argillaceous member described and named by Jacobs (1938, p. 20) as the Brigham Hill "gray-wacke."

Cheshire Quartzite

The Cheshire Quartzite is typically a pure, massive white quartzite; however, the lower portion of the formation, which is exposed in the Monkton area as the core of an eroded anticline, is much less massive and shows bedding. It has a porous texture and contains interbedded argillaceous and schistose layers.

The massive quartzite that forms the resistant hogback ridges in the Monkton area is light gray to brown in color and has undergone a high degree of recrystallization. Cady (1945) describes the dense quartzite unit as being about 350 feet thick with a higher unit of interbedded quartzite and dolomite grading into the overlying Dunham Dolomite.

The lower part of the formation weathers brown, is more porous, and much less massive than the upper unit. Cady (1945) describes the unit as a "schistose brown quartzite," and feels that its thickness is indeterminate because the contact with the underlying Mendon Formation is obscure at all points where a measurable section is available. He does believe, though, that it is probably not less than 500 feet, which is in accord with observations made by the writer. This part of the Cheshire Quartzite is of importance since it is the horizon in which the kaolin is found, and is described in detail throughout this report. These layers of thick, massive quartzite containing porous and permeable horizons showing bedding and cross-bedding, are interbedded with schistose layers of thinly laminated graphitic, quartz-sericite schist.

Generally, the lower unit of the Cheshire grades downward into the Moosalamoo Member of the Mendon Formation by an increase in the amount of feldspar, muscovite and graphite. The top unit of the Cheshire is transitional into the Dunham Dolomite through a series of carbonate interbeds.

Dunham Dolomite

The Dunham Dolomite very probably plays no role in the origin of the kaolin, but it is a part of the regional structure and, for this reason, is described in this report. However, on an old town map of Monkton, a kaolin pit is indicated north of the village of Monkton Ridge and within the area of the anticlinal structure in which the kaolin deposit is located. Since the anticline plunges to the north here, the location indicated on the old map places the deposit in the overlying Dunham Dolomite. The writer searched for this old pit and found a small depression located in the area of the Dunham Dolomite on the west side of the height of land; however, excavation or core drillings would be necessary to determine the presence of kaolin here. The Dunham Dolomite may be very thin at this location, and the kaolin, if present, could very well be associated with the underlying Cheshire Quartzite.

According to Cady (1945), the Dunham Dolomite is "mainly a siliceous buff-weathered dolomite containing well-rounded sand grains irregularly distributed." The weathered surface shows abundant sand grains giving the rock a sandpaper-like surface. Occasionally the dolomite shows excellent cross-bedding, and the quartzite beds in the formation become thicker and more prevalent as the contact with the overlying Monkton quartzite is approached.

Monkton Quartzite

The Monkton Quartzite is briefly described since its only appearance is where the salient of Cheshire Quartzite has been thrust upon the Monkton Quartzite just west of the kaolin deposits. This is the location of the Monkton thrust fault.

The formation is distinguished by its red color, and is at the locality from which it derives its name. Along the thrust fault the Monkton is a massive quartzite which forms a resistant ridge with the bedding dipping at 50–70 degrees to the east. A few thin beds of reddish to purplish shale are interbedded with the quartzite. Ripple marks and mud cracks on the bedding surfaces of the shaly members, and cross-bedding in the quartzites are common.

Glacial Deposits

The bedrock of the region is overlain by an irregular mantle of glacial debris or ground moraine. This material consists of boulder clay (hard pan), sand, and gravel distributed partially in kame- and drumlin-like features, but mainly in thick irregular masses. The hillside in which the kaolin occurs is covered with anywhere from ten to twenty feet of this glacial material.

Structure

The major structural features of the Monkton area trend north-south. The four major types of structures in the area are: synclinoria, anticlinoria, thrust faults, and a normal fault system.

The two synclinoria are basic in the structural and stratigraphic geology of the region. They have a common north-south axis and are separated along this axis by what Cady (1945) calls the Monkton "cross anticline." The word culmination describes the feature more graphically, as it is a structure from which the two synclinoria, named Middlebury and Hinesburg, plunge in opposite directions. The Middlebury synclinorium plunges southward from the latitude of the village of Monkton, and is bounded by Snake Mountain on its west limb and the Green Mountains on its east limb. The Hinesburg synclinorium plunges northward from the latitude of the village of Monkton and is bounded by Lake Champlain on the west and the Green Mountains on the east.

Anticlinoria or structural highs occur east and west of the synclinoria. The Adirondack Mountains form a structural high on the west, and the Green Mountain anticlinorium forms a structural high on the east.

Two major thrust faults occur west of the Green Mountains. They are the Champlain thrust along Lake Champlain, and the Hinesburg thrust, in this area, which parallels the west base of the Green Mountains.

A north-south trending belt of normal faults is common on the western border of the region. According to Cady (1945) the belt consists of a set of longitudinal faults which are down-thrown to the east-southeast and strike north-northeast. Cady feels that these faults in the region of Lake Champlain are closely related to a similarly orientated joint system in the Adirondack Precambrian crystalline basement, and are apparently limited in distribution to a tectonic zone in the immediate vicinity of the Adirondacks. The Champlain thrust and associated structures lie mainly in a zone of movement concentrically above the zone of strong normal faulting that lies in and peripheral to the Adirondack massif.

A traverse of the structures from the Green Mountains west to the Monkton thrust reveals the following features: the Starksboro syncline, the Hogback anticline, the Pond Brook syncline, the eroded, overturned anticlinal structure in which the kaolin occurs, and the Monkton thrust where the Cheshire Quartzite is thrust upon the Monkton Quartzite (Fig. 4). The two adjoining folds, consisting of the Hogback anticline and the Starksboro syncline, plunge both north and south, and in the northeastern part of the Town of Monkton the Cheshire Quartzite of the Hogback anticline plunges beneath the overlying Dunham Dolomite; the structural relationship of the dolomite to the quartzite is well shown in many places. The Hogback anticline can be classified as an asymmetrical anticline with the strata of the west limb dipping almost vertically and the strata of the east limb dipping about 70 degrees to the east (Plates 5, 6). The fact that the Hogback

anticline plunges beneath the Dunham Dolomite to the north and is completely surrounded by it, is evidence for this anticlinal structure. Field evidence tends to favor a normal synclinal valley of Dunham Dolomite bordered by two eroded anticlinal ridges of quartzite overturned to the west.

Plate 1. A southwesterly air view across the kaolin deposit to the west limb of the overturned and eroded anticline and the Monkton thrust line.

Plate 2. View north from within the overturned and eroded anticline to where it plunges to the north.

The steep escarpment immediately east of the kaolin deposits appears to be the eastern limb of an overturned and eroded anticline (Plate 1). Field evidence indicates that the kaolin is located in this overturned and eroded anticline which has been subjected to movement along the Monkton thrust (Plate 2). The east limb of the deformed anticline consists of the upper member of the Cheshire Quartzite which is massive, crystalline, and forms a resistant ridge with a steep escarpment facing to the west. This escarpment is due to differential weathering and possibly represents a longitudinal fault which is common in overturned structures of this type. The center or axis of the anticline is made up of the

DIAGRAMMATIC SKETCH OF
SURFACE GEOLOGY TO
THEORIZED CROSS-SECTION
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GREEN
MOUNTAINS

MENDON SERIES

DUNHAM DOLOMITE €dh

CHESHIRE QUARTZITE €c

DOLOMITE €dh

DUNHAM

GREEN MOUNTAIN COMPLEX

IGNEOUS ACTIVITY?

ZONE OF KAOLINIZATION

EAST MONKTON

€c

CHESHIRE QUARTZITE

VT. KAOLIN CORP.

€Md

€c

€dh

WINOOSKI DOLOMITE

€W

€M

MONKTON QUARTZITE

€M

N

CHAMPLAIN THRUST
NORMAL FAULTING
MONKTON THRUST?
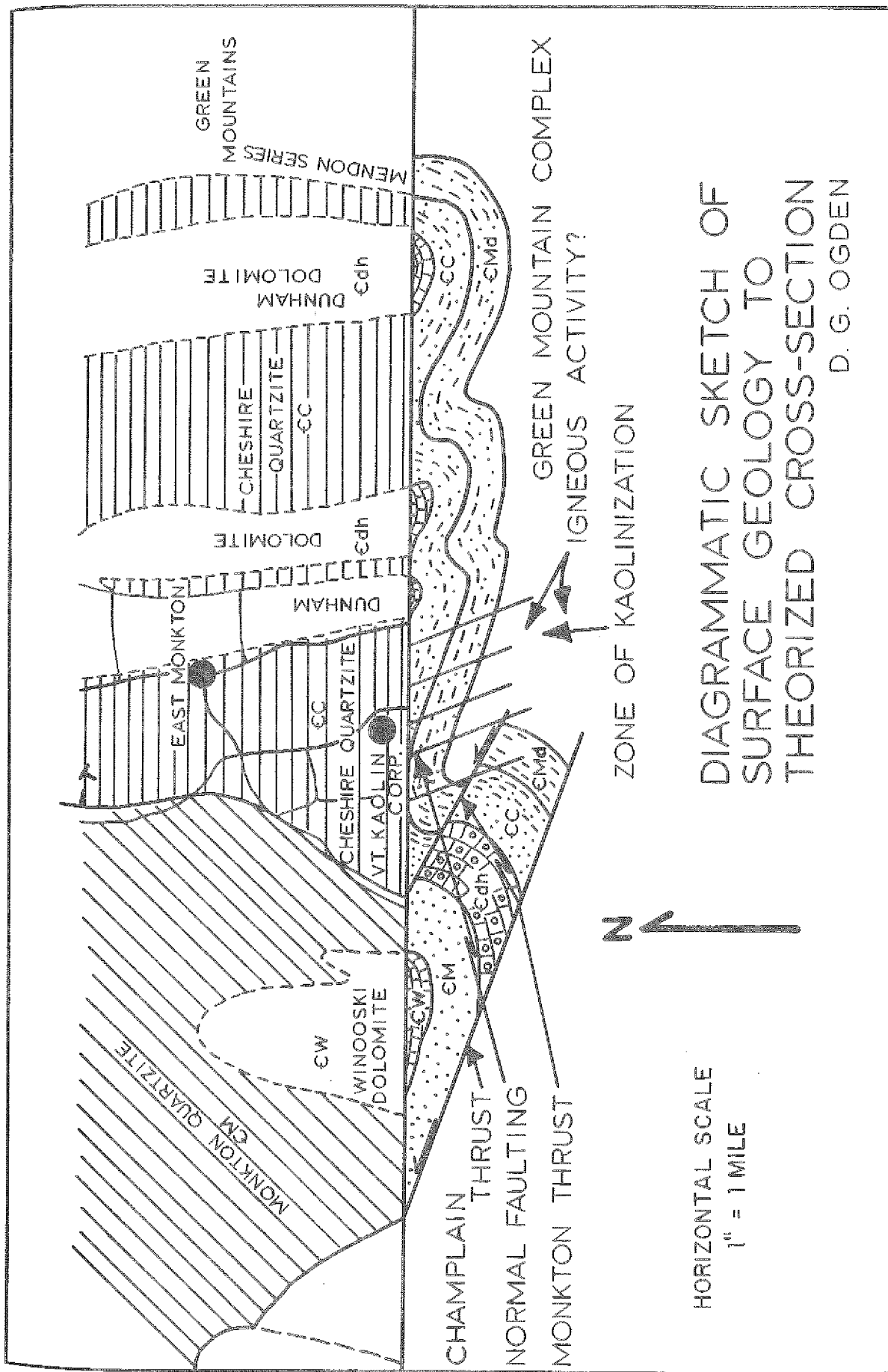
HORIZONTAL SCALE
1" = 1 MILE

Figure 4.   Diagrammatic cross-section of the regional geology.

lower members of the Cheshire Quartzite; however, where this is not in evidence, the writer suspects that the upper member of the Mendon Formation occupies the core of the anticline, in which the upper or western kaolin body is found. The lower or eastern kaolin body has been exposed by excavations, which reveal what appears to be the lower member of the Cheshire Quartzite (Plate 3). Here the exposures consist of layers of massive quartzite with excellent bedding features,

Plate 3. A southwesterly view of the kaolin deposit.

layers of friable, kaolinic quartzite, and thin layers of phyllitic, argillaceous material, which for the most part have been altered to kaolin. It is the strata of this section which have been invaded by hydrothermal solutions, resulting in the formation of kaolin by alteration and replacement.

Plate 4. View east of the steep escarpment-like ridge east of the kaolin deposit. The east limb of the overturned and eroded anticline.

The western limb of this overturned and eroded anticline consists of the upper member of the Cheshire Quartzite (Plate 4). The quartzite here has a very steep dip of 60–80 degrees to the east, and forms the contact

with the Monkton Quartzite at the Monkton fault. The anticline as a whole plunges to the north and in the region north of Monkton Ridge it plunges beneath the Dunham Dolomite.

The presence of the Monkton thrust is made evident by truncation of the quartzite beds, and by the abnormal superposition of widely separated stratigraphic units. Cady (1945, p. 574) traces the thrust fault from a southward plunging anticline one mile north-east of New Haven village northward to the north-plunging anticline at Monkton Ridge. He states that "the massive gray facies and also a brown, rather schistose facies of Lower Cambrian Cheshire Quartzite, found in most of the hilly area trending southward through the center of Monkton into northwestern Bristol township, overlie the thrust plane. Along the thrust between the latitude of Monkton village and the north boundary of New Haven township the red Lower Cambrian Monkton Quartzite outcrops immediately west of the Cheshire."

Plate 5. Exposed strata on the escarpment-like ridge east of the kaolin deposit. The dip of this east limb of the overturned and eroded anticline varies from 30 to 70 degrees.

Plate 6. Exposed strata on the escarpment-like ridge east of the kaolin deposit. The overturned fold in this massive Cheshire Quartzite indicates the anticlinal structure of which it is a part.

[14]

The great stratigraphic separation of these two formations is clearly indicated by an examination of the normal sequence of Lower Cambrian formations represented by the northward-plunging anticline north of Monkton Ridge. In the northern part of the town of New Haven, south of the Monkton area, the Monkton Quartzite immediately west of the fault has been covered by the Cheshire Quartzite. Farther south the quartzite has even been thrust onto the Winooski Dolomite, which lies stratigraphically above the Monkton.

Igneous Masses and Dikes

North of the Canadian border in Quebec, a group of igneous rocks, occurring as stocks and dikes, have intruded beds as young as Devonian in age. These igneous intrusives comprise the features known as the Monteregian Hills. Similar igneous rocks cut the Ordovician sediments throughout Vermont, and are exceptionally numerous in the Champlain Valley.

In Vermont, the region about Burlington and Shelburne Point is most prolific in dikes, which appear to be similar in composition to the rocks of the Monteregian Hills. These dikes are extremely interesting because they tell something about the foundation upon which the deformed sediments of the Champlain Valley rest. Some of the dikes contain inclusions or xenoliths that have been carried from below by the magma which rose to fill the fissures. Many of these xenoliths consist of granitic rocks and gneisses of the old metamorphic rocks beneath the Cambro-Ordovician beds and therefore indicate a source of magma below the Precambrian complex.

The dike intrusions in both Quebec and the Burlington-Shelburne areas are represented by two varieties of igneous rocks. One is a feldspathic porphyry or trachyte called *bostonite*, and the other consists of dark basic rocks classified as *camptonites*, *monchiquites*, and *fourchites*. These two groups of intrusive rock make up a majority of the dikes found in both areas. The dikes of the Champlain Valley assume a radial pattern with the apparent source located in the area of Shelburne Bay. This pattern of dikes would seem to indicate the presence of an igneous body not far from the surface.

Associated with the numerous dike intrusions are the alkaline intrusions (essexite and syenite) of the Monteregian Hills in Quebec, Barber Hill in the Champlain Valley at Charlotte, and the Cuttingsville intrusive complex composing "Granite Hill" in the Green Mountain anticlinorium. These intrusive bodies all appear to be of the same magmatic province, and therefore associated with the same period of intrusion. It is assumed here that Barber Hill and the Champlain Valley dikes are related to the Monteregian intrusives. The syenite mass forming Barber Hill may very well play an important role in the hydrothermal theory expressed in this report. It is important to note that the Barber Hill intrusion lies at the west extension of the east-west culmination separating the Middlebury and Hinesburg synclinoria, possibly indicating an extension of the syenite mass at a relatively shallow depth to the Monkton area. The small hill of syenite is located in the town of Charlotte approximately six miles west of the town of Monkton Ridge. This syenite intrusion along with the bostonite-camptonite dike association suggests the possibility that essexite as well as other syenite masses exist within the region between the Champlain thrust and the Green Mountains. Since Barber Hill was only recently recognized as a syenite intrusion, other magmatic bodies may exist as similar hills yet to be discovered.

The intrusive body at Cuttingsville is located within the central part of the highly deformed Green Mountain anticlinorium about ten miles southeast of the City of Rutland. This intrusion has a syenite-essexite composition, a cross-cutting relationship with the surrounding country rock, an oval surface exposure, and high angle contacts, all indicating that it is of the same structure and much the same composition as Barber Hill in the Champlain Valley.

The Monteregian Hills, for the most part, lie west of the deformed area and the Vermont intrusions have invaded the slightly deformed rocks of the Champlain Valley and the highly deformed rocks of the Green Mountain anticlinorium. These intrusions are not noticeably disturbed or affected by deformation, which indicates that their emplacement followed the major folding and faulting. The heat of these magmatic bodies and the volatiles and solutions emanating from them created thermal metamorphic changes in the intruded strata and provided the hydrothermal conditions on which the theory advocated in this report is based.

THE KAOLIN DEPOSIT
General Statement

Kaolin is best described by the geologist as a rock composed essentially of the kaolin minerals. Mineralogically the term was once used to refer to a single clay mineral, but the word is now used as a group name for at least four separate clay minerals: kaolinite, nacrite, dickite, and halloysite.

The definition of the kaolin minerals as proposed by Ross and Kerr (1931, p. 152) has generally been accepted. According to them "kaolin is understood to be a rock mass which is composed essentially of a clay material that is low in iron and usually white or nearly white in color." The kaolin-forming clays are hydrous aluminum silicates of approximately the composition $2H_2OAl_2O_32SiO_2$, and it is believed that other bases, if present, represent impurities or absorbed materials.

They also suggest that the name kaolinite be kept for the characteristic mineral of kaolin, and that the other two chemically similar minerals of the kaolin group be called nacrite and dickite.

Kaolinite is the abundant mineral that makes up the kaolin deposit at East Monkton. Kaolinite is often well-crystallized in its hexagonal form; however, many investigators have found that kaolinic minerals are poorly crystallized. This appears to be the case with the kaolinite from the East Monkton deposit where it has a vermicular structure. Whether this occurrence should be known by a different species name or whether it is a disordered kaolinite appears to be open to choice. Grim (1953) states that there are probably many gradations from well-crystallized kaolinite to that of complete randomness in the *b* direction and in the population of aluminum directions; so it appears doubtful that a specific name should be applied.

The minerals of the kaolin group, kaolinite, dickite, nacrite and halloysite, consist of sheet units which are continuous in the *a* and *b* directions and stacked vertically in the *c* direction. Any variation among the members of this group lies in the manner in which the layers are stacked and in the position of the aluminum atoms in the possible positions for them in the octahedral layer.

The charges within the structural units of the kaolin group are balanced and it has been shown that there is very little substitution within the lattice structures. The group represents a crystal structure where one gibbsite sheet is condensed with one silica sheet, forming a stable non-expanding type of crystal lattice. The clays composed of the non-expanding lattice structure are said to possess moderate surface activity and generally form relatively freer flowing systems in water. On the other hand, clays composed of the expanding crystal lattice are capable of high collodial activity and hydration, producing plastic and gel-like water systems.

History of Commercial Development and Economic Problems

A brief history of the commercial development of the kaolin industry at East Monkton will give an idea of the extent to which the deposits have been mined over the past years. For the most part the operations have been carried out on a small scale, and few figures as to actual tonnages are available. Also, there seem to be very few remaining records of production, mill procedure or drilling logs.

J. Muzzy (1813) records the first operation in 1792, when a Mr. Stephen Barnum discovered kaolin on his property while he was searching for iron ore which had been mined for some time near the Bristol town line south of his land. The white material or "putty" had been discovered earlier, but it seems that Mr. Barnum

was the first to classify it as kaolin, and it is believed that the deposit was the first to be found in the United States. During the early 1800's Mr. Barnum mined considerable quantities of the kaolin, selling it in Troy and Albany, New York.

During the early 1800's the Monkton Argil Company was incorporated and an attempt was made to mine the kaolin for crockery manufacture. This company is said to have mined several hundred tons of kaolin, and as this operation progressed a Mr. J. Muzzy kept a record of the strata in one of the company's pits. This appears to be the only past record of a drill log in the East Monkton area. The description has to be condensed, but it does contain some interesting and amusing facts. Strata consisting of quartz, "graphic granite" and feldspar were encountered with layers of kaolin and fine sand between them. It is interesting to note that "pure" kaolin at a depth of sixteen feet was said to be of a much superior quality to that found nearer the surface.

In the Annual Report of the Vermont State Geologist, Adams (1848) describes the kaolin deposit as being very extensive, and that in 1843, forty tons were taken to Burlington where it was sold for forty dollars per ton and was used for pottery and furnace linings.

According to Collins (1955), the kaolin works at the crossroads in East Monkton came under the management of B. F. Goss of Vergennes, and was worked until the late 1880's (known as Goss and Falbott, Goss and Gleason, and the American Kaolin Company) (Plates 7, 8). The washed kaolin was used as a paper filler. The production figures of the American Kaolin Company during the 1800's are as follows: 1883–1962 tons, 1884–2412 tons, 1885–4494 tons, 1886–2468 tons, 1887–4508 tons, 1889–2386 tons and 1890–1975 tons.

In the early 1900's (Collins, 1955), another operation under the name, American Paper Clay Company, was conducted near the present site of the Vermont Kaolin Corporation (Plate 9) by a Mr. O. N. Williams. Mr. Williams is said to have spent 12,000 dollars for the construction of his kaolin works, and that production during the year 1914–1915 was ten tons a day, for which ten dollars a ton was received. The area owned by Mr. Williams was north of and adjacent to land owned by Frank E. Bushey, which is now owned by the Vermont Kaolin Corporation. Mr. Williams had some drilling done to determine the amount of kaolin present, but all the records were lost when the buildings burned down in the early 1920's. It has been reported, however, that twenty to twenty-five holes were drilled to a depth of around one hundred feet, and that kaolin was found at the bottom of all of them. Perkins (1906) reports that six six-inch borings varying from 41 to 174 feet in depth were sunk to determine the thickness of the deposit. However, even the deepest hole failed to reach the base of the deposit, and so, such information is quite useless.
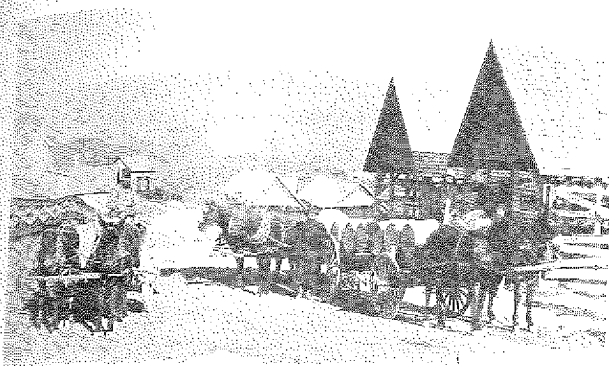
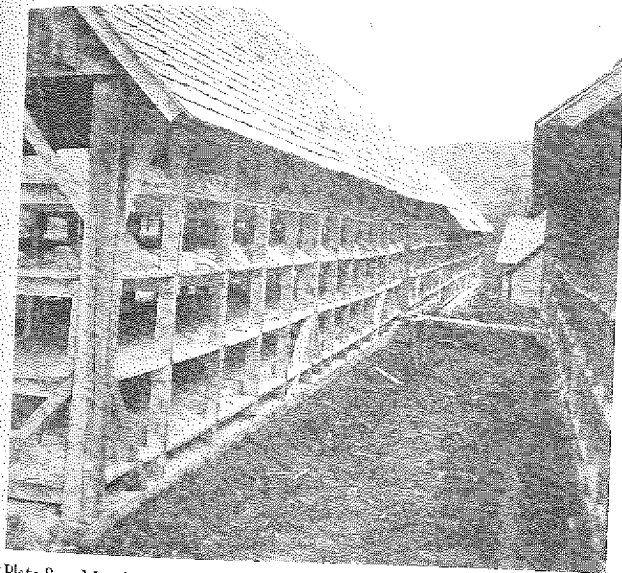Plate 7. Monkton Kaolin Works, Goss & Gleason, Proprietors.

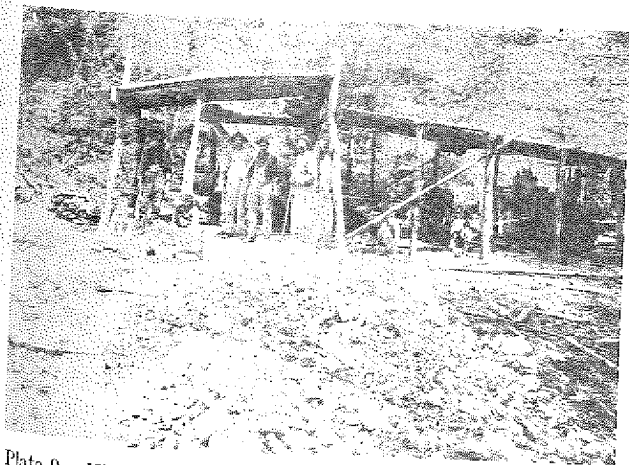Plate 8. Monkton Kaolin Works (drying sheds), Goss & Gleason, Proprietors.

Plate 9. View of the Kaolin operations at Monkton in 1905. Mr. Carl Laird, foreman, on left. (Vermont Geological Survey)

especially since there is no record of where the drilling took place or what types of material were encountered. Mr. Williams operated the kaolin works until the

1920's (Collins, 1955) when he sold out to the Continental Clay Company owned by Mr. R. T. Vanderbilt. Mr. Vanderbilt held the property and allowed a Mr. Carl Laird to mine kaolin intermittently.

During the 1930's the property was purchased by Frank E. Bushey and son, Leon V. Bushey, and the last active kaolin production at East Monkton was carried on by Frank E. Bushey and Son until 1944. It is reported that they produced about a thousand tons annually, which were sold to the Rutland Fire Clay Company. Mr. Leon V. Bushey retained the mineral rights to most of the kaolin-bearing property until July, 1956 when they were purchased by the Vermont Kaolin Corporation.

During the summer of 1959 the Vermont Kaolin Corporation began construction of storage facilities and a processing plant near the site of the former Bushey home (Plate 10). Extensive exploratory and laboratory work was conducted to determine the quantity and quality of the kaolin.
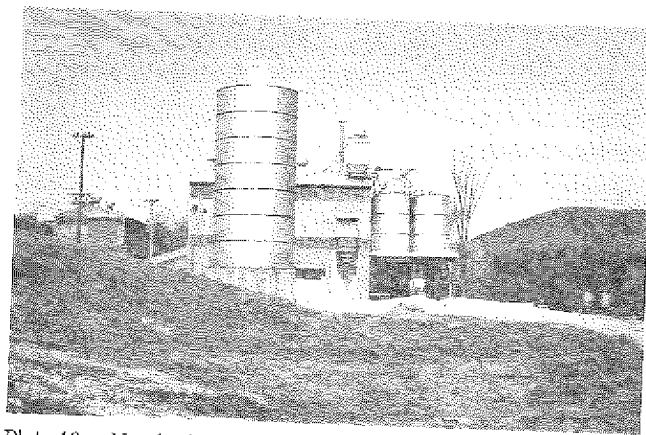

Plate 10. Northerly view of Vermont Kaolin Corporation plant—1967. (C. G. Doll)

The method of processing the crude clay was to be either the wet or the dry method, or a combination of these. A pilot mill was put in operation to evaluate the efficiency of the dry process. This process consisted of pulverizing the crude clay, and then obtaining particles of desired fineness by having them lifted from the grinding chamber by air currents, while the coarse particles were rejected from the upward stream of fines by whizzer-type separators. The air flotation plant consisted essentially of a rolling type dryer, a high side Raymond roller mill whizzer separator and a cyclone collector and bin.

The Vermont Kaolin Corporation planned to be in production by the fall of 1960. The product was to be a high alumina kaolin, a high silica kaolin, and pure silica. The Corporation expected to produce one hundred tons per day which would be trucked to a railroad siding at New Haven Junction where it was to be stored and tagged for shipment.

[17]

The records of the Vermont Kaolin Corporation contain numerous different evaluation reports written during the period in which the Corporation attempted to develop the deposit. The figures and procedures presented here are for the most part from a report by the General Manager, George B. Guillotte (Guillotte, 1966).

Total ore put through the dry process plant from 1961 to 1966 was 18,400 tons which yielded 9,235 tons of clay. The waste product was reported to contain about 91% quartz, 3% iron and titanium oxides and 6% clay.

The mill was operated only two or three times yearly on a 24-hour basis. The days of continuous operation varied from 12 to 20 days, depending upon the time required to fill the storage facilities on the railroad at New Haven Junction.

When the mill was continuously operated, it averaged 57 tons per 24-hour operating day, which was only 57% of the 100 tons per day capacity for which it was designed.

The dry mill products did not meet the specifications for the paper or ceramic industries. Sales were made to manufacturers of soft rubber products and some of the product was sold to grain companies using kaolin for pelletizing livestock feed.

Due to the nature of the deposit, a great deal of difficulty was encountered in trying to separate the kaolin from the quartzite by the dry process.

The next separation attempt was a wet process. Since the largest consumers of kaolin in New England, New York and Canada are paper mills for filler and coater, research was then directed toward a water-washed clay that would be acceptable.

A small wet mill was built and approximately two years were devoted to test operations designed to bring all specification requirements to the level for paper maker acceptance.

First of all, the clay was found to be too coarse in particle size. The paper makers require 80% minus 2 micron particle size for filler and 90% minus 2 micron particle size for coater clay. The average particle size of the material taken from the Hatch Pit was as follows: 99% minus 25 micron, 96% minus 18 micron, 95% minus 15 micron, 84% minus 10 micron, 80% minus 7 micron, 61% minus 5 micron, 58% minus 4 micron, 41% minus 3 micron, 27% minus 2 micron and 10% minus 1 micron.

To realize good recovery of the minus 2 micron material, it was necessary to devise a means of reducing the particle size of the coarse fraction. The Minerals Industries Corporation of America, Lowell, Massachusetts, developed a grinding device which appeared capable of doing the job. In addition to reducing particle size, the grinding step also freed occluded particles of quartz, FeO, and TiO minerals which had to be released to improve brightness and reduce abrasion.

The small wet mill was built to produce one ton of finished clay per hour. The mill was operated from December of 1965 to June of 1966. A large part of the output during this period was wasted because of experimental drying, balancing feed rates, varying pulp densities and checking out different amounts and types of reagents.

A small amount of material having a brightness of 81, abrasion of 26, 80% minus 2 micron particle size and flowability at 70%, was produced. All attempts to upgrade this material to a brightness of 86 or better and 90% minus 2 micron particle size failed.

The wet process did prove that the degritting section could eliminate the quartz to acceptable levels. The problem then was the failure of the clay to gain acceptable brightness, due to the inability to eliminate minerals contributing to off-color and reflectance.

The flotation and bleaching process followed standard clay beneficiation as practiced on the transported clays of Georgia and South Carolina. Because of minerals resulting from the origin of the kaolin at East Monkton, additional treatment was needed to attain desired results. The discoloration caused by FeO and TiO minerals was apparently solved by the beneficiation process; however, the major problem was the presence of a graphitic material (Plate 16). This graphitic material represents the thin layers of phyllitic rock (graphitic, quartz sericite schist) that was not completely altered to kaolin. These small graphitic, shaly particles were very evident in the waste taken out by flotation. Future consideration of this kaolin deposit for high-grade products will have to deal with the problem of eliminating the graphitic material.

During December of 1966, the mill equipment at East Monkton and the bagging facilities at New Haven Junction were purchased by the White Pigment Corporation of Proctor, Vermont. A plant has been built at New Haven Junction to process white, high calcium marble from the Shelburne Formation east of Middlebury.

Future economic consideration of the reserves of kaolin and kaolinic quartzite in the East Monkton area should include the potential of high silica sand and the extraction of aluminum oxide.

Extent of the Deposits

The belt of the lower member of the Cheshire Quartzite with which the kaolin is associated, extends from the Bristol town line northward toward the village of Monkton Ridge where the anticlinal structure plunges to the north. In the vicinity of East Monkton the anticlinal structure has been gouged by glacial action, exposing the lower members of the Cheshire Quartzite and possibly the upper members of the Mendon Formation. This area of about two miles in length and three-

quarters of a mile in width contains the kaolin-bearing strata which are entirely buried by glacial drift. In addition, a deposit of kaolin is located on an old map of Monkton, about half a mile north of Monkton Ridge. This location is unusual since the old map places it in a ridge underlain by the Dunham Dolomite. A small pit on the hillside is probably the only evidence of the reported kaolin deposit, and further investigations by borings are necessary before the presence of this deposit can be confirmed.
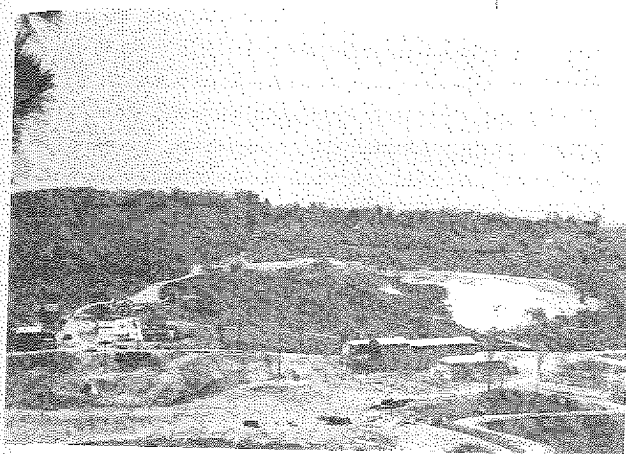

Plate 11. The Vermont Kaolin Corporation plant and the hillside in which the kaolin occurs. The excavation is in the lower kaolin body (Hatch Pit). The upper kaolin body follows along the ridge of the hill.
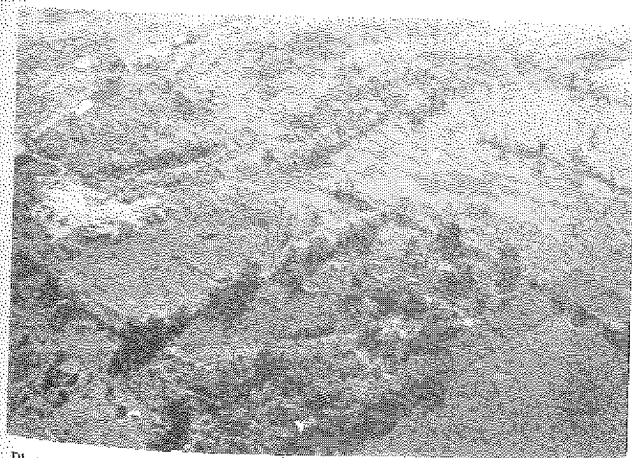

Plate 12. The hill in which the kaolin occurs, showing the lower kaolin body (Hatch and Bushey Pits) and the upper kaolin body (old pits at the bottom of the picture).

The area of commercial interest is close to three-quarters of a mile square, and is located approximately half a mile north of the "Monkton Orebed." A slope immediately west of the old Bushey homestead, the site of the Vermont Kaolin Corporation office, contains the two kaolin bodies that have been most thoroughly investigated to date (Plate 11, 12). The lower or eastern

kaolin body has been excavated, exposing the kaolin and the quartzite formation in which the kaolin occurs. The content of this excavation varies from a relatively pure to a sandy kaolin interbedded with kaolinic and massive quartzite layers. The material from this lower body was used for laboratory tests and for testing in the pilot plants.

To evaluate the kaolin deposits, Guillotte (1966) reports that 8,211 lineal feet of backhoe trenching to depths of 15 feet have been made. In addition, a total of 412 drill holes (2 diamond drill holes, 9 churn drill holes and 401 auger drill holes) aggregating 17,312 vertical feet have been put down. It is reported that 217 of the holes drilled penetrated clay-bearing material to indicate six separate ore bodies containing 11,149,200 tons of kaolin in 22,298,400 tons of clay-bearing material.

The properties and tonnages estimated are as follows:

Eastern (lower) ore body (Hatch and Bushey Pits)	1,095,700
Western (upper) ore body (500 feet west of Hatch Pit)	1,500,000
Central LaFountain	279,000
South—Central LaFountain	431,000
Northwest LaFountain	1,465,000
Jewell—Blanchard	6,378,500
Eastern LaFountain (not evaluated)	
"Tons of Clay available" =	11,149,200

The eastern and western ore bodies are the only ones considered in this report as they contained the only open pits for inspection.

According to an earlier report by W. P. Mould (1959), the estimated available tonnage in the two explored bodies is as follows: the smaller and lower body (eastern ore body) pitches gently to the east and covers a minable area of 13.8 acres. The known ore thickness ranges from 40 to 75 feet. The estimated crude clay tonnage is 1,742,824 tons, and on the basis of 30 percent recovery by mining, 523,000 tons of crude clay can be sent to the mill. The larger body (western ore body), outcropping near the height of land on the western border of the company property, is more steeply inclined to the east. Only the thick layer that outcrops at the northern end of this section of the clay horizon is considered in the estimate of tonnage. The minable outcrop is taken as 750 feet long by 450 feet wide, and assuming the layer to be 350 feet thick along the dip, the tonnage present is greater than 5.5 million. At 30 percent recovery it was calculated that 1,650,000 tons of crude clay could be sent to the mill.

It is noteworthy that in 1965 Guillotte (1966) reports that 8 holes were drilled in the bottom of the Hatch pit which penetrated to substantially greater depths than

did previous drill holes located near the same coordinates. Hole No. 16 penetrated white clay for 92 feet below the previously established bottom of the clay (54 feet); hole No. 11 penetrated 70 feet below the previously established clay limit (30 feet), and hole No. 18 penetrated 18 feet below the previously established limit. These holes are spread over a distance of 220 feet from east to west, giving a cross section of considerable depth of reported kaolin. No attempt was made to prove this extension north-south along the strike of the deposit.

All drill holes were surveyed by chain and transit to establish elevations and coordinates. All holes were plotted on a 100 feet to 1 inch scale. Some areas were detailed on a 50 feet to 1 inch scale, and a map of 300 feet to 1 inch showing hole locations was drawn up. All of these maps and the log books are in the records of the Vermont Kaolin Corporation.

Mr. Jason Wark, working under the direction of Dr. Charles G. Doll, State Geologist, did considerable electric resistivity testing on the Vermont Kaolin property during the summers of 1958 and 1959 (Wark, 1968). Anomalies obtained indicated areas of clay which were later substantiated by drilling on the eastern, western, and Jewell-Blanchard ore bodies (Wark, 1968).

The Vermont Kaolin Corporation carried on an extensive drilling program, but more knowledge still is needed as to the geologic and structural relationships between kaolin-bearing ground and non-kaolin bearing ground. The type of drilling done and the difficult formations encountered, produced estimated reserves that are at best "guesstimates." Any other exploration program will certainly have to follow the rule of quality control, in that core readings should include a mineralogical analysis with further emphasis on percentages, color tests, and particle size distribution.

Geologic Relationship to Other Known Vermont Deposits

Along the western base of the Green Mountains there are a series of kaolin deposits extending from Bennington, Vermont, northward to the deposit at East Monkton. This broken chain of kaolin deposits includes occurrences at Brandon (Forest Dale), Rutland, North Clarendon, South Wallingford, Tinmouth, North Dorset and Shaftsbury. The total distance of this chain of deposits is over one hundred miles.

It is evident that the kaolin deposits are arranged along a zone of faulting, and a definite relationship seems to exist between the faulting and the kaolin. A consideration of the faults, therefore, would seem important in a study of the origin of the kaolin deposits. The fault zone contains both earlier thrusts and later normal faults.

According to Burt (1928), most of the deposits at Bennington lie on the downthrow side of the branches of the so-called Green Mountain Front fault and very close to it. All of the kaolin deposits are associated with the thrust faulting and/or the normal faulting.

The kaolin at East Monkton is definitely associated with a zone of faulting. The deposits lie on the upthrow side of the Monkton fault and within the highly faulted easterly dipping quartzite strata of an eroded, overturned anticline which has been broken and thrust westward onto younger strata. It would seem logical to assume a like origin for the kaolin deposits at Bennington, along with the other known deposits between these two areas. In all cases, the deposits are located within the Cheshire Quartzite, which is relatively free of feldspar. A theory applicable to the origin of one deposit, then, should hold at least partially true for the others occurring in this discontinuous chain along the western border of the Green Mountains. The evidence presented in this report for a hydrothermal origin of the kaolin at East Monkton differs widely from some earlier reports of the formation of kaolin by the weathering of feldspar in place. The other kaolin occurrences throughout the state have not been closely examined by the writer, but it seems very probable that their origin is much the same as that hypothesized for the East Monkton deposit.

Structure of the Formation in Which Kaolin Occurs

The kaolin at East Monkton is contained in two separate horizons of what appears to be the lower member of the Cheshire Quartzite. These horizons outcrop on the north-south trending hillside as easterly dipping limbs of an eroded and highly fractured, overturned anticline.

As previously mentioned, the two ore bodies have been explored extensively by the Vermont Kaolin Corporation. An examination of the surface outcrops, the bottoms of trenches, the excavations, and the borings, shows that the hillside throughout its length is composed of easterly dipping beds of the lower Cheshire Quartzite striking in a northeast direction. The eastern limb of the eroded anticline is resistant, forming the prominent escarpment directly east of the ore bodies, while to the west and center of the anticline appear the more porous and permeable members of the quartzite showing excellent bedded and cross-bedded features. Within this lower part of the formation are thin interlaminations of black material of a phyllitic nature; a graphitic, quartz-sericite schist. The porous, sandier appearing members and the phyllitic layers are in turn contained within layers of the massive, crystalline quartzite. The strata in many places are highly faulted, resulting in many displaced layers shattered into a friable condition. The kaolin occurs in the center of this anticlinal struc-

ture mentioned above. It occurs finely disseminated in voids among quartz grains in the altered quartzite, as thin replaced layers between the quartzite strata, and also as veins following planes of fracture.

The most extensive deposits of kaolin so far discovered are the two easterly dipping ore bodies that outcrop on the hillside. The lower and smaller body ranges from 40 to 75 feet in thickness, with the extent of the deposit down dip unknown. This ore body is represented by excavations known as the Bushey and Hatch pits. Both of these pits have recently been opened further and the south face of the Bushey pit shows an excellent undisturbed cross-section of the formation in which the kaolin occurs (Fig. 5) (Plates 13, 14, 15, 16). The layers of quartzite and kaolinic quartzite at this location dip approximately 18 degrees to the east; however, the dip of this lower ore body varies at other places along the strike to as much as 30 degrees to the east, suggesting movement by faulting and the resulting adjustment of fault blocks.

The larger body of kaolin outcrops near the height of land on the western border of the company property.

Plate 14. South face of the Bushey pit showing a close view of the massive quartzite layer.

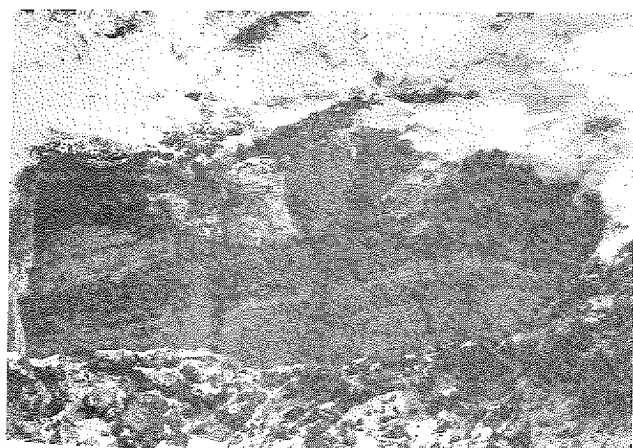Plate 15. Excavation in the Hatch pit (lower kaolin body) showing reworked kaolin.

Plate 13. South face of the Bushey pit showing the undisturbed structure of the kaolin deposit. The massive quartzite layer through the center dips approximately 18 degrees to the east. The white deposit is snow.
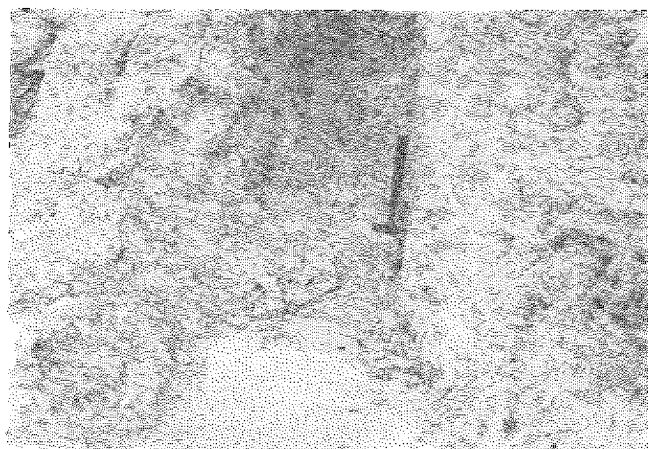
Plate 16. Closer view of reworked kaolin in the Hatch pit.

Along the strike of this ore body are old excavations in which the kaolin is not now exposed. No new excavations have been made, but borings indicate that the strata here (approximately in the area of the apex of the overturned anticline) are more steeply dipping to the east, as would be expected. The strata of this ore body are approximately 450 feet thick and dip from 40 to 50 degrees to the east. Borings and test samples reveal a kaolin of somewhat different nature from that of the lower ore body. W. P. Mould (1959) found that during the drilling of this area pebbles and cobbles were encountered, possibly indicating a conglomeratic horizon in which this body of kaolin occurs. Also, in this ore
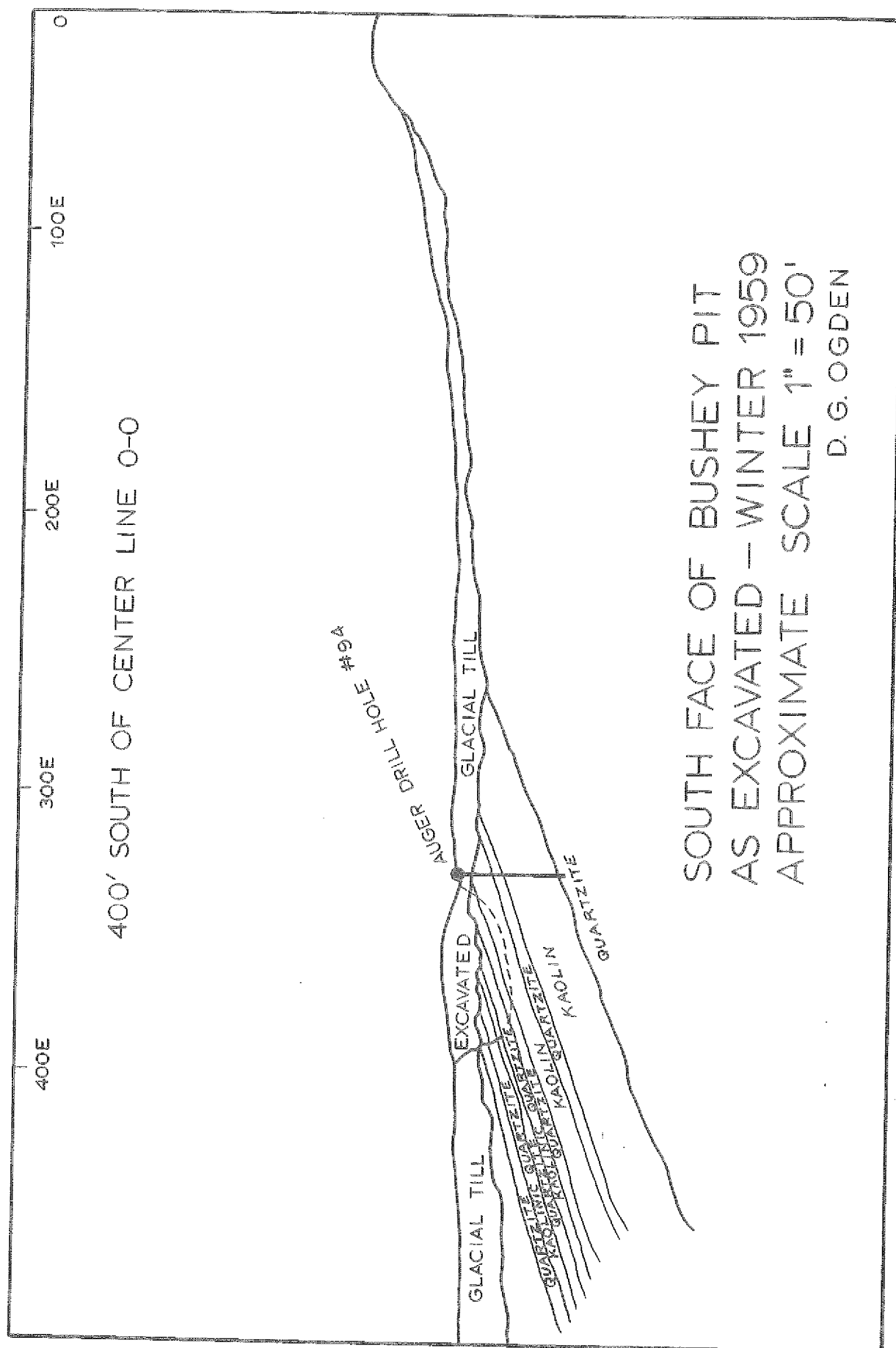
Figure 5. Structural sketch of the south face of the Bushey pit.

body a purplish-red kaolin has been found along with a shaly material of the same color, a chemical analysis of which shows a higher content of alumina than is found in the lower kaolin body. This might indicate that this ore body lies in the upper member of the Mendon Formation. Since this area represents approximately the apex of the overturned anticline, the assumption is that the Mendon Formation is close to the surface here; however, an assumption of this sort cannot be checked until the kaolin body is excavated or drilled and the strata examined carefully.

According to Bain (1925) an even later group of faults or readjustments of the earlier structures took place with the movement almost at right angles to the earlier normal faults. This same type of movement has taken place locally within the area of the kaolin deposits, as indicated by borings. Just west of the road that passes by the Vermont Kaolin Corporation office, a north-south traverse of borings shows kaolin at considerable depth, abruptly terminated by quartzite lying just beneath the surface, apparently suggesting an east-west fault.

More structural evidence indicating that the kaolin deposits are located in a zone of deformation, is the jointed character of the quartzite wherever it occurs with the kaolin. The joint planes appear to fall in a definite system, but an exact pattern cannot be determined because of the cover of glacial drift. In outcrops there are always at least two directions of jointing present, which generally meet at right angles, one striking parallel to the fold axis and the other normal to it. They generally show quite steep dips, which makes the determination of the true bedding difficult in the massive members of the quartzite.

The deformational effects are also exhibited by zones of granular fracturing in the quartzite, in which the quartzite has been rendered friable and, in places, even crumbled to a dust. All of these deformational effects play an important role, since they undoubtedly have directed the course of emanations and circulating waters during the hydrothermal activity.

Descriptions of the Kaolin

The lower or eastern kaolin body has been partially excavated, resulting in good exposures of the kaolin in both the Hatch and Bushey pits. The Hatch pit consists mostly of reworked material since a period of active mining was followed by a slumping of the walls after activities ceased. As a result, the deposit is a mixture of pure kaolin, very sandy kaolin, and kaolin containing fragments of kaolinic and massive quartzite. The western face or footwall of the deposit remains relatively undisturbed, displaying a massive and resistant quartzite which determines the position of the footwall. Occurring throughout the kaolin in this pit are numerous

fragments of a milky quartz vein. The vein is approximately four inches in thickness and lies in chunks throughout one area of the pit. Its cloudy appearance may, in part, be due to disseminated kaolin indicating that the formation of the kaolin took place during the deposition of the quartz vein. In addition, the chunks of vein quartz are extensively pitted, the pits containing white, hard kaolin, which is further suggestive of contemporaneous deposition.

Within this same ore body and along the strike southward is the Bushey pit. The walls of this old pit have also slumped; however, a recent cut along the south face clearly reveals the structure of the ore body and the kaolin in place. The kaolin occurs as void fillings in the kaolinic quartzite, as intercalations, as lenticular forms, and as fillings in fractures. For the most part, the kaolin is white and appears to be relatively pure. Some of the layers of kaolin, which apparently have resulted from the alteration of the phyllitic members of the quartzite formation, contain graphitic areas of shaly material representing incomplete alteration (Plate 17).

Plate 17. Outcrop of easterly dipping Cheshire Quartzite approximately a mile north of the kaolin deposit. Much of this outcrop consists of layers of black phyllitic rock (graphitic, quartz sericite schist).

When examined in thin section, this black, leached shaly material shows a mass of sericite and voids in an argillaceous groundmass. Most of the formation consists of kaolinic quartzite that retains the original bedding and cross-bedding, in which replacement has progressed to such a degree that the material is of an extremely sandy nature which can be easily removed. The kaolin and the sugary silica sand definitely appear to be the result of the alteration of the bedded quartzite. Layers of a hard, cream-colored kaolinic quartzite of a porous, fine-grained variety are also found in the formation.

An important feature in this cut (Bushey Pit) is the presence of milky quartz veins throughout the deposit

(Plates 18–23). Once again, it is evident that this secondary quartz was formed in the quartzite with the kaolin mineral and sericite, in the form of irregular veins, stringers, and pockets. The milky appearance of the quartz, in particular the crystals along the outer edges, can be interpreted as evidence for the formation of the kaolin during deposition of the secondary quartz vein.

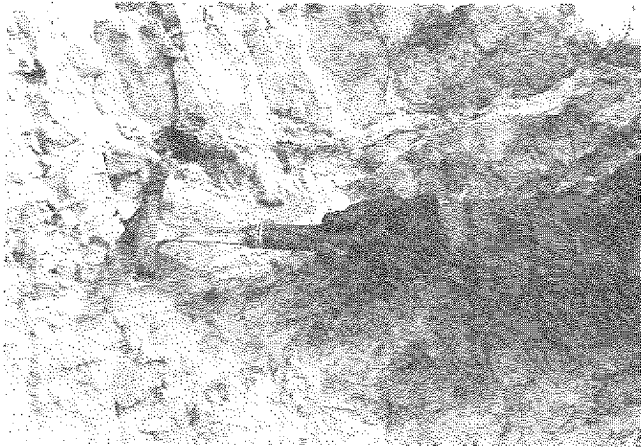The upper or westerly kaolin body has not recently been excavated, and so, all that is known of the nature

Plate 18. South face of the Bushey pit (lower kaolin body) showing intercalated layers of kaolin. The hammer points to an area of black graphitic material that has not been completely altered to kaolin.
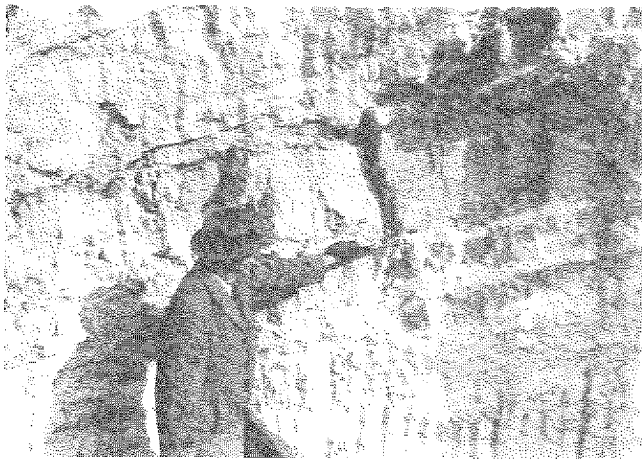

Plate 19. South face of the Bushey pit showing layers of massive quartzite, intercalated layers of kaolin (hammer), and bedded kaolinic quartzite.

of the kaolin there is derived from the material obtained by auger drilling and trenching. Drilling investigations indicate the presence of a thick deposit which has been discussed previously. This deposit is intercalated with beds of quartzite, kaolinic quartzite, and kaolin, much the same as in the lower body. However, the kaolin of this occurrence appears to be of a different kind, as it has a variety of colors ranging from red to purple.
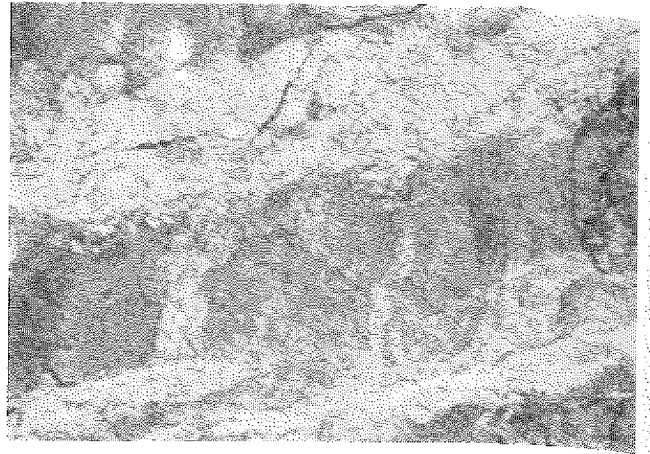
Plate 20. Close view of south face of the Bushey pit showing layers of kaolin, and kaolin filling the fractures in the quartzite layer.

Plate 21. South face of the Bushey pit showing jointing and cross-bedding in the quartzite, intercalated layers of kaolin, and kaolinic quartzite at the bottom of the picture.

Plate 22. South face of the Bushey pit showing the thin intercalated kaolin layers. These layers once consisted of a phyllitic rock subsequently altered to kaolin.

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Plate 23. South face of the Bushey pit showing cross-bedding in the massive quartzite layer. Kaolin has replaced the narrow more porous layers exhibiting the bedding. The cross-bedding is tangential to the base of the stratum indicating a normal position of the layers.

Pieces of a reddish purple, shaly material are quite common. As is the case with the leached shaly material in the lower body, an examination of this rock in thin section reveals mostly sericite in an argillaceous groundmass.

Chemical analyses of the kaolin (Table 2), though of

TABLE 2
CHEMICAL ANALYSES OF CRUDE KAOLIN
EAST MONKTON

	Lower Body Hatch Pit	Lower Body Bushey Pit	Upper Body Purple-X
SiO_2	63.570	65.480	59.380
TiO_2	0.340	0.240	0.480
Al_2O_3	22.473	23.528	25.180
Fe_2O_3	1.250	0.992	4.741
MgO	0.260	0.340	1.560
CaO	0.008	0.001	6.005
Na_2O	1.004	0.236	1.122
K_2O	3.474	2.895	2.509
P_2O_5	0.007	0.020	0.011
Loss on Ign.	6.600	7.380	5.460
Total	98.988	101.112	100.376

Analyses by Mr. F. J. Tupper, chemist for the Vermont Kaolin Corporation

BENNINGTON

SiO_2	56.98
TiO_2	1.67
Al_2O_3	28.52
Fe_2O_3	.76
MgO	.77
CaO	.10
K_2O	1.41
Loss on Ign.	9.25
Total	99.46

Analysis by the Merrimac Chemical Company (Jacobs, 1940)

not much practical value, show that the kaolin contains a fair amount of impurities, that it approaches rather closely the composition of sericite, and that the accompanying quartzite parent rock controls the content of silica. The analysis of the colored kaolin from the upper body shows a higher iron content and a slightly higher alumina content than similar analyses of the kaolin from the lower body, very probably indicating a different type of host rock. It is interesting to note that all three of the East Monkton analyses (Table 2) have high potassium content and are low in water which is suggestive of a sericite alteration product (Table 3).

TABLE 3
CHEMICAL ANALYSES OF KAOLINITE,
MUSCOVITE AND SERICITE

Kaolinite		Muscovite (Ideal)	
SiO_2	46.5	SiO_2	45.2
Al_2O_3	39.5	Al_2O_3	38.5
H_2O	14.0	K_2O	11.8
		H_2O	4.5
Total	100.0	Total	100.0

Sericite (Number 44-Windgalle)

SiO_2	51.83
Al_2O_3	28.77
Fe_2O_3	2.63
FeO	1.91
MgO	0.54
CaO	0.63
K_2O	8.63
Na_2O	0.98
H_2O	3.77
Total	99.69

Analyses from E. S. Dana (1893, p. 618 and 686)

Age of the Kaolin

The age of the kaolin can be placed in a certain range of time only by determining its relationship to the bedrock, glacial deposits, and regional igneous activity.

The quartzite in which the kaolin occurs is obviously older than the kaolin since there is definite evidence of the replacement of the silica cement in the quartzite member, the alteration of the interbedded phyllitic rock, and the deposition of kaolin in the joints and fractures of the quartzite. The kaolin occurs as a result of deformation, and its development would have to follow the last major faulting movements. Bain (1925) feels that the latest faulting along the Green Mountain front was during Triassic and Jurassic times. According to this supposition, therefore, the kaolin at East Monkton would have been developed during or following Triassic time.

The deposits are definitely pre-Pleistocene as is evi-

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denced by the overburden of glacial drift. Since the deposits lie in the path of glacial action, and it is evident that the glacier deeply eroded much of the fractured and overturned anticline in which the kaolin occurs, it is reasonable to suppose that glaciation has removed a considerable part of the upper portion of the kaolin beds.

The Barber Hill syenitic intrusion in Charlotte and the numerous dikes in the Champlain Valley all cut the Ordovician rocks of the area, and in many places cut the Champlain thrust. Most of the dikes are vertical and undisturbed, indicating that they are associated with the intrusion of magma following the Paleozoic orogenies. This would place the age of the intrusives not earlier than Triassic times. In support of this hypothesis, a radioactive age determination made of the camptonite dike in the Willard's Ledge quarry at Burlington, places its age in the Triassic period (Urry, 1937). Since the theory of kaolin origin at East Monkton in this report is based on the hydrothermal influence of hidden magmatic bodies, and since emanations from these intrusions are considered to have resulted in the formation of the kaolin, it is reasonable to assume that the formation of the kaolin has approximately the same age as the regional intrusive action.

It seems highly probable that the kaolin deposits along the Green Mountain Front at Bennington, Brandon, and East Monkton resulted from the same process and, therefore, are of the same age, yet the Brandon kaolin is associated with lignite which has been dated as Miocene by a study of the contained plants. However, since the deposit is of a sedimentary nature, in that it consists of strata of kaolin and lignite, the writer feels that it is secondary and the result of a reworked nearby primary deposit.

According to the above data, the age of kaolin formation at East Monkton is post-Permian and pre-Pleistocene, probably Triassic in the writer's opinion.

PETROGRAPHIC STUDY OF THE KAOLIN AND THE QUARTZITE

The Kaolin

Samples of kaolin from both the lower and upper ore bodies have been examined petrographically, in an attempt to determine the kaolin mineral, or minerals, present. The use of the petrographic microscope for such a determination has definite limitations but can be of considerable value. Optical properties are difficult to determine because of the very fine-grained character of the kaolin, hence some of the results obtained may be misleading. Fortunately the kaolin is relatively pure and, except for the presence of silica sand, is of a monomineralic character, so that the optical values obtained give a good clue as to the kaolin mineral present. Most of the kaolin consists of relatively large kaolinite

"worms" of a vermicular nature, which can easily be detected when using the high power objective. These "worms" yield good optical data, and their properties definitely establish them as kaolinite.

The presence of these colorless "worms" of kaolinite permits an accurate determination of the indices of refraction, the birefringence, and the optical sign of the kaolinite. The use of index of refraction liquids showed the kaolinite to be slightly over 1.561, which is within the range of the three indicies possessed by the monoclinic mineral. The birefringence is weak, which is the case with kaolinite, since the difference between the highest and lowest indices (alpha and gamma) is small (.005). Its relief is low, and the interference colors are low, in the grays and whites. The kaolinite is too fine grained to obtain an interference figure; however, Grim (1953) states that the alignment of kaolinite particles parallel to the a and b axes will result in the appearance of a good interference figure by which the positive optical sign and the axial angle can be determined. The most distinctive clue in determining that the kaolin mineral is kaolinite, however, is the particular accordion or worm-like characteristic of the mineral.

A good deal of sericite is also found in the kaolin, and can be distinguished from the kaolinite by its higher relief, strong birefringence and negative sign. The sericite occurs as minute shreds and scales. It is formed as a result of hydrothermal alteration, and much of it appears to be the result of the alteration of the phyllitic layers within the quartzite formation.

A petrographic examination of the kaolin reveals the presence of quartz, kaolinite, and hydrous mica or sericite (possibly illite), the major accessory minerals being tourmaline and zircon.

The Vermont Kaolin Corporation submitted a sample of the kaolin to the Colorado School of Mines Research Foundation, Inc., for an X-ray diffraction analysis. The analysis indicated that the natural clay contained kaolinite and alpha quartz as the major minerals present, and a hydrous mica as a minor mineral. The kaolinite produced a sharp, well-defined diffraction pattern indicating good quality "crystallites" of relatively large size. The silica present was found to be alpha quartz "crystallites" of good quality and of sufficiently large size to give a clear, sharp diffraction pattern.

During August of 1966, a sample of dark brown clay was taken from an area in the Hatch Pit and was X-rayed by the Anglo-American Clays Corporation of Sandersville, Georgia. The analysis was only semi-quantitative, but the result was as follows: kaolinite, illite, and vermiculite each formed 25–30% of the sample, while the remainder consisted of an amorphous material and a mineral intermediate between vermiculite and illite. Since quartz was conspicuous by its absence and is very

common in the surrounding rocks, the dark brown material may originally have been a small basic intrusive, subsequently altered to the clay minerals.

Heavy and Light Mineral Examination

This study was made to determine the heavy minerals present in the kaolin deposit at East Monkton, and at the same time to examine the light minerals for feldspar or partially decomposed feldspar. Samples of sandy kaolin from both the Hatch and Bushey pits of the lower ore body were examined.

The heavy minerals are for the most part the minerals of the parent rock which survived destruction by weathering, abrasion, or interstratal solution; they are the accessory minerals of the quartzite and are marked by a higher than average specific gravity. The heavy minerals in the original quartzite are quite rare, and form less than 1.0 percent of the sandy kaolin. In order to study them it was necessary to isolate them from the bulk of the light minerals with which they are associated. This separation was performed by the standard method which is described below.

Approximately a 100-gram sample of each was taken from a representative layer in the kaolin deposits. The sample was dried and then washed on a 200-mesh sieve to wash out the clay particles. The remaining sand was then dried and passed through a 60-mesh sieve to obtain a fairly uniform size. About 10 grams of this fraction were placed in a 125-milliliter separatory funnel with approximately 25 milliliters of the heavy liquid tetrabromoethane (specific gravity 2.950). The sample was agitated and stirred thoroughly and allowed to settle for a few hours. After all of the heavy minerals had apparently settled out, the heavy and light fractions were removed, washed with acetone, and dried on filter paper. Both the heavy and the light minerals were mounted on slides that were covered with a thin coating of caedax (index of refraction 1.54). The slides were then allowed to dry before examination with the petrographic microscope.

The sandy kaolin from the two pits of the lower ore body contains the following heavy and light minerals.

HEAVY MINERALS

The following heavy minerals were found in order of decreasing abundance: zircon, tourmaline, magnetite and ilmenite, leucoxene, garnet, ankerite, rutile and epidote.

LIGHT MINERALS

Quartz only.

Generally a heavy mineral analysis is used for cases of stratigraphic correlation because, theoretically, each stratigraphic unit differs to some degree from every other stratigraphic unit in the character and abundance of its suite of accessory minerals. The heavy mineral assemblage also proves useful as a guide to the kind of source rock from which the sediments were derived. In the case of the sandy kaolin at East Monkton, it is obvious that the source rock is the quartzite that has undergone a replacement process, but the occurrence of different varieties and forms of tourmaline may be an indication of the conditions which brought about the replacement within the quartzite member.

The varieties of tourmaline might possibly be a clue to the nature of the conditions to which the source rock was subjected. They appear as irregular fragments, well-rounded grains, euhedral grains, and what appears to be overgrowths on other well-worn or fragmental tourmaline grains. Varieties found are brown, tan, olive-drab, pink, blue and colorless. The euhedral varieties may have been transported without showing signs of wear. However, the overgrowths on the well-worn varieties strongly indicate an authigenetic origin. The source of the material necessary for the formation of the tourmaline, a complex boron aluminum silicate, may have a relationship to the conditions under which the quartzite rock was replaced. The tourmaline, other than that of detrital origin, may be the result of pneumatolytic or solution activity from igneous intrusives.

An examination of the light mineral fraction shows both angular and rounded quartz grains. No feldspar fragments were found in the three separations made. The fact that no feldspar was found in the sandy kaolin indicates that the quartzite layer contained very little detrital feldspar, or that what feldspar was present has been completely replaced by the process of kaolinization. The quartzite is certainly not of an arkosic nature in any of the occurrences observed by the writer. This fact further supports the hypothesis that the kaolin is a result of the replacement of the phyllitic layers and the silica cement in the quartzite and not the decomposition of feldspar.

The Quartzite and Casts of Kaolinic Quartzite

The quartzite in which the kaolin occurs comprises members of the lower Cheshire and, possibly, upper Mendon formations. In many horizons there is quartzite which has not been attacked by hydrothermal activity, and is of a white to brown, massive and sometimes vitreous nature, in places even resembling vein quartz. A thick layer of this massive quartzite separates the two kaolin ore bodies. Also within the kaolin ore bodies are layers of this massive quartzite. A layer of this quartzite exhibiting massive and jointed characteristics is exposed in the Bushey pit. Much of the massive quartzite, particularly the more granular and porous variety has distinct bedding, which is further emphasized by excellent cross-bedding. The horizontal and cross-bedded layers of the porous quartzite contain

kaolin, which was introduced by the solutions passing through these connected openings. These narrow layers represent porous and permeable avenues through which solutions passed. These solutions also deposited secondary silica cement and a carbonate cement which were, in turn, replaced by kaolin.

The formation in which the kaolin occurs is interlaminated with argillaceous layers of a phyllitic rock, perhaps best described as a graphitic, quartz-sericite schist. This material has for the most part been replaced by kaolin occurring in relatively pure, vein-like layers.

The most extensive member of the kaolin-bearing formation is the kaolinic quartzite. This porous and friable rock consists of kaolin and detrital quartz grains. The quartz grains maintain their original positions, and the kaolin occurs in the interstices between these grains. It is noted that the quartz grains have a marked vertical elongation, and that this elongation, along with a definite lineation of the grains, is preserved throughout the rock. The original structure of the quartzite and the cross-bedding features are preserved in this way. The kaolinic quartzite appears to contain over 60 percent kaolin, and makes up most of the lower ore body.

The kaolinic quartzite has been studied in detail, and casts of it have been taken for examination under the microscope. The casts were obtained by applying a layer of collodion over a smooth surface of the porous quartzite. The dried collodion was peeled off, revealing a perfect cast of the solution cavities among the primary quartz grains; these casts show definitely that the material around the elongated and lineated quartz-grains has been replaced by the kaolin. The cementing material of the Cheshire Quartzite appears to be secondary silica, and this secondary silica was acted upon by hydrous alumina solutions in forming the kaolin which now occupies the interstices. Since ankerite has been found in the petrographic study of the sandy kaolin, there is a chance that some of the cement was a carbonate; at any rate the cementing medium has been replaced by kaolin.

Thin Section Analyses*

The purpose of this study was to examine the mineral content of the quartzite, and to examine the texture of the kaolinic quartzite. A series of rocks consisting of the massive quartzite and the different varieties of kaolinic quartzite have been examined in thin section with the petrographic microscope.

The massive quartzite is composed almost entirely of strained quartz grains and a fine-grained silica cement. This massive quartzite contains very few feldspar grains

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* Specimens from Bushey pit, unless otherwise stated.

and only a few well-rounded detrital heavy minerals. The kaolinic quartzite, however, contains some authigenetically formed tourmaline, and some of the porous and very fine-grained rock contains authigenetic feldspar, for the most part microcline.

The texture of the kaolinic quartzite becomes evident when examined microscopically. There are numerous voids formed as solution cavities around the primary quartz grains. It appears that the secondary silica cementing material has been removed, leaving the quartzite rock in various degrees of porosity. In some horizons the replacement has been so complete that the remaining primary quartz grains and kaolin result in a highly friable rock.

A description of hand specimens and accompanying thin sections follows:

HAND SPECIMEN K1

Massive quartzite from the resistant layer separating the two kaolin ore bodies. It is of a light gray color with brown streaks of ferric oxide and contains a few cavities that appear along bedding directions; however, the bedding is not apparent.
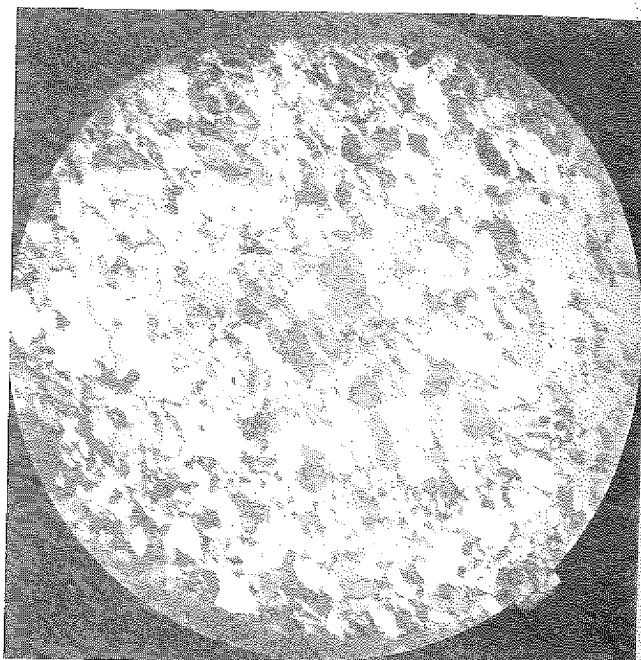

Plate 24. Thin section of specimen K 1 (20 power). Massive Cheshire Quartzite with the primary quartz grains showing undulatory extinction and lineation.

Thin Section—K 1 (Plate 24)

Quartz—large elongated grains showing definite lineation and undulatory extinction. These large grains are set in a very fine-grained secondary silica cement.

Zircon—few and rounded.

Tourmaline—few and rounded. Olive-drab and brown.

Iron Oxide—specks of ferric oxide.

This section contains a few rounded cavities within the mass of the fine secondary quartz grains.

HAND SPECIMEN K 2

A massive quartzite from a resistant layer in the Hatch pit (same as quartzite in Bushey pit). This rock shows well-defined bedding and cross-bedding. The bedding is exemplified by the porous nature of certain horizons; these thin layers have become a kaolinic quartzite, since the numerous voids contain kaolin. The porous, thin layers, are white, and the massive rock is light to dark gray with brown streaks.

Thin Section—K 2

Quartz—large elongated grains showing lineation and undulatory extinction, cemented by small secondary quartz grains.

Zircon—few and rounded.

Tourmaline—few and rounded. Olive-drab and brown.

Garnet—few.

Ilmenite and Leucoxene—few patches.

Rutile—few fine needles.

Iron Oxide—specks along bedding planes.

This section shows the transition from massive layering to porous layering. The porous layers contain many rounded solution cavities within the secondary silica cement.
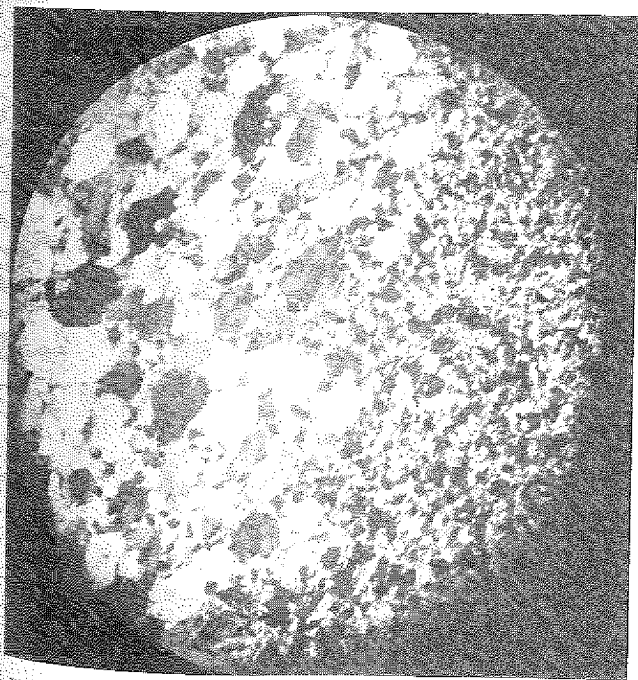

Plate 25. Thin section of Specimen K 3 (20 power). Shows the contact between a fine-grained kaolinic quartzite layer and a coarse-grained massive quartzite layer. Note the numerous voids in the kaolinic quartzite.

HAND SPECIMEN K 3

This specimen shows the contact between a fine-grained kaolinic quartzite layer and a coarse-grained, massive quartzite layer, both containing numerous cavities. The fine-grained kaolinic layer is white, and the coarse-grained, more massive layer, is a dark gray.

Thin Section—K 3 (Plate 25)

Quartz—the coarse, massive layer consists of large, elongated grains, many bounding each other and others separated by a fine-grained secondary silica cement.

Tourmaline—olive-drab, brown and pale yellow to colorless.

Zircon—few and rounded.

Sericite—within the coarse, massive layer as veinlets, and also surrounding a few of the large grains.

Leucoxene—few patches.

In this section the fine-grained kaolinic quartzite contains many irregularly rounded solution cavities. The coarse, massive layer contains rounded cavities occurring in the secondary silica cement.

HAND SPECIMEN K 4

This is a specimen of fine-grained, kaolinic quartzite. A very porous member of the quartzite group with kaolin occupying the voids.

Thin Section—K 4 (Plate 26)

Quartz—fine-grained primary quartz surrounded by even finer grained secondary quartz.
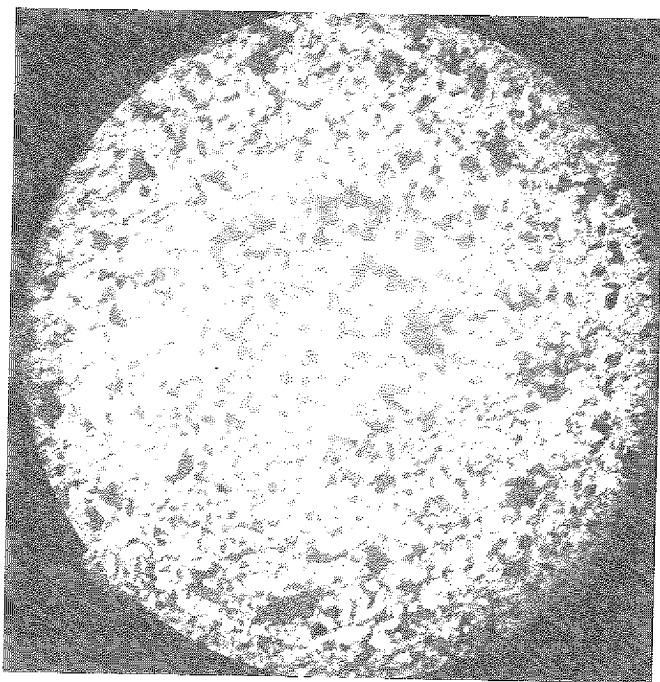

Plate 26. Thin section of specimen K 4 (20 power). Fine-grained kaolinic quartzite. Numerous voids represent solution cavities.

Tourmaline—olive-drab, brown and yellowish. Some are angular and have a euhedral tendency.

Zircon—few and well-rounded.

Sericite—found as veinlets and also surrounding some of the quartz grains.

This section of fine-grained kaolinic quartzite contains many voids representing solution cavities. Their form indicates that they were once occupied by fine-grained, secondary quartz.

HAND SPECIMEN K 5

This is a specimen of the fine-grained kaolinic quartzite with the porosity of some layers more evident than that of others. The specimen is cut by a vein of low-temperature quartz which is cloudy and granular in appearance, even to the naked eye. The outer layer of the quartz crystals is milkier than the outer layer of the other crystals, suggesting the assimilation of kaolin at the time of their contemporaneous formation. As in the other kaolinic quartzite specimens examined, the voids are filled with kaolin.
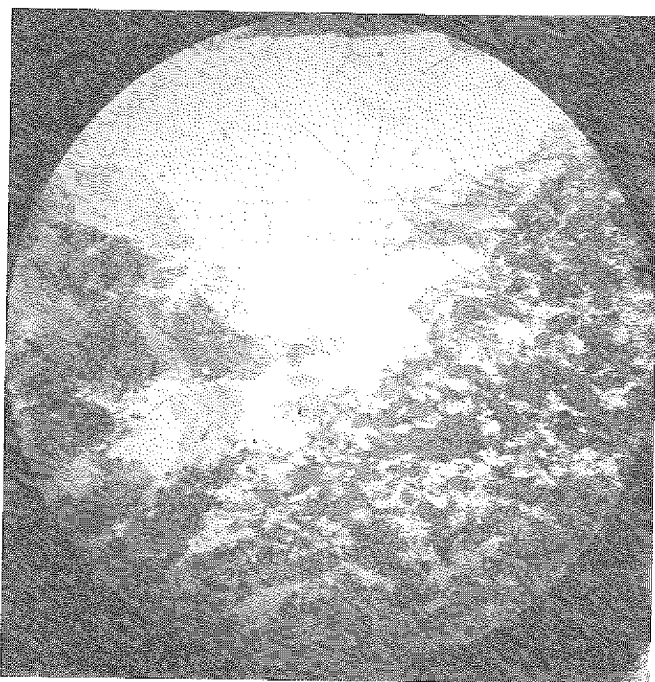

Plate 27. Thin section of Specimen K 5 (20 power). Fine-grained kaolinic quartzite in contact with a vein of low-temperature quartz. The large vein-quartz grains are cloudy. The numerous cavities in the kaolinic quartzite contain kaolin.

Thin Section—K 5 (Plate 27)

Quartz—fine-grained with a scattering of larger grains.

Tourmaline—some rounded and others angular, suggestive of authigenetic overgrowths. Olive-drab and dark blue in color.

Leucoxene—some greenish to bluish.

Zircon—few and well rounded.

Sericite—in fine veinlets.

This section of fine-grained kaolinic quartzite contains many solution cavities believed to have been occupied by secondary quartz cement. The quartz vein consists of very large, elongated quartz grains. The grains are fractured to the point where they appear granular. The fractures are filled with fine-grained quartz.

HAND SPECIMEN K 27

This is a specimen of fine-grained, very porous white, kaolinic quartzite from a horizon in the Bushey pit. It contains many thin veins of opal-like quartz. The rock exhibits many dendritic manganese stains. The many solution cavities render it very porous and consequently of lessened weight.

Thin Section—K 27, number 2 (Plates 28, 29)

Quartz—a few, large elongated grains, but mostly fine-grained, angular quartz that appears to have been greatly fractured.

Feldspar—authigenetic feldspar grains appearing to have filled the voids between the fractured quartz grains. The feldspar is mostly microcline with some orthoclase or possibly adularia.

Sericite—numerous shreds occurring between the grains.

Tourmaline—angular, olive-drab, reddish-brown and dark blue in color.

Zircon—few and rounded.

Iron Oxide—numerous specks.

This section of porous, fine-grained kaolinic quartzite is of importance in that it contains authigenetic feldspar in the many voids, and is cut by thin veins of what appear to be opal. Under high power, the vein material is isotropic and contains many white flakes which appear to be kaolin, suggesting contemporaneous formation. It is notable that none of the feldspar appears decomposed or undergoing kaolinization. This specimen is pertinent to the theory that the hydrous aluminum silicate solution, under varying conditions, formed either sericite, feldspar, or kaolinite.

HAND SPECIMEN K 31

This is a specimen of greenish black shaly rock found in the horizons of pure kaolin. It can be found in varying degrees of alteration and leaching from a black phyllitic state to pure kaolin. In many of the horizons it occurs in friable plates that are gray in color and quite slippery. This rock, which is also reddish in the upper ore body, represents the laminated phyllitic members found throughout the quartzite formation. It was previously described as a graphitic, quartz-sericite schist.
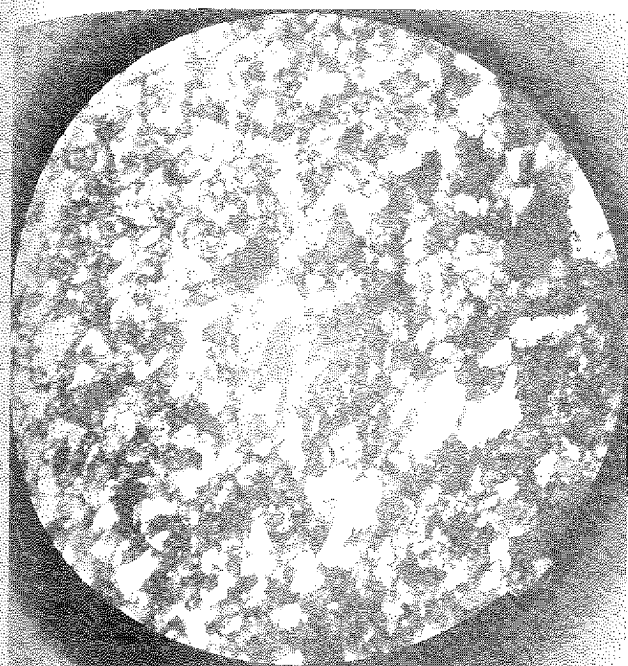
Plate 28. Thin section of specimen K 27 (20 power). Fine-grained, porous, kaolinic quartzite. Shows numerous cavities containing authigenetic feldspar, mostly microcline.
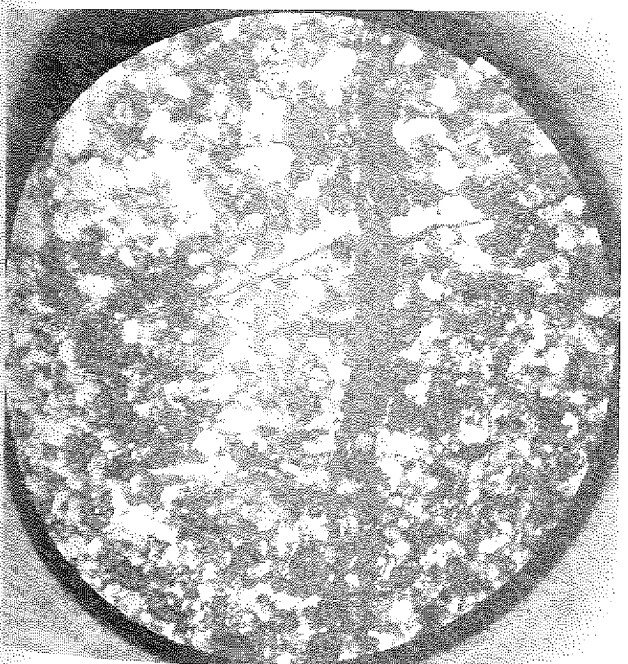

Plate 29. Thin section of specimen K 27, number 2 (20 power.) Same as the above plate except for the presence of a vein of opal. The opal vein contains flakes of kaolin.

Thin Section—K 31

Sericite—a mass of small lath-shaped sericite.
Zircon—few and rounded.

Leucoxene—few patches.

This section of leached rock is now completely composed of sericite shreds and flakes, except for numerous voids. The voids were very likely once occupied by leucoxene. The rock is extremely fine-grained and the high power objective is required to determine the sericite grains.

ORIGIN OF THE KAOLIN

General Statement

The association of the kaolin deposits with a zone of fracturing and faulting is of considerable economic importance, since the horizontal extent of the kaolin may well be directly related to the zone or zones of deformation. It is important from a commercial viewpoint that the source from which the kaolin was derived be determined. If the kaolin was carried into the zone of deformation from a superficial source or derived from the weathering of a feldspathic rock *in situ*, it might bottom before a profitable mining depth could be reached. On the other hand, if the kaolin originated from a deep-seated source, it is to be expected that the deposits persist to depths beneath the limit to which kaolin can be profitably mined.

There have been many hypotheses suggested for the origin of kaolin. These hypotheses fall into one or the other of two classes, depending upon whether the source of the kaolinizing agency was shallow or deep-seated. Kaolin formation can be a significant indicator of earth processes. It is now evident that kaolin forms through a range which involves at one extreme the action of compressed water vapor at a temperature of several hundred degrees centigrade, and at the other extreme, the action of atmospheric agencies at ordinary surface temperatures. The relationship of kaolin to the magmatic process has recently become a topic of interest, since it has been found that the last of the fluids and vapors of a magma may react with the wall rock to form kaolin. It has also become evident that, with time, kaolin deposits of hydrothermal origin can become distinguishable only with difficulty from kaolin deposits formed under atmospheric conditions, that is, those of supergene origin.

The presentation of this report relative to the origin of the kaolin at East Monkton has been developed along the following lines:

1. The various ways that kaolin in other areas is believed to have originated.

2. The evidence indicating the manner in which the East Monkton deposits have originated.

3. Conclusions drawn relative to the origin of the kaolin at East Monkton as inferred from evidence cited.

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Review of Previously Presented Theories

The section in this report on "Previous Work" pretty well covers past ideas concerning the origin of the kaolin at East Monkton. These suppositions varied from the decomposition of "graphic granite" to the generally accepted theory of the weathering of a feldspathic quartzite or "sandrock" in place. Earlier mention of the kaolin at East Monkton has been based on the assumption that it must have developed from the residual weathering of a feldspathic rock by the well-known process of kaolinization. In this reasoning, the quartzite formation in which the kaolin is found had to be feldspathic. Much of this type of thinking has developed from the fact that Ries (1927), who can be called one of the pioneers in clay study, defined kaolin as a white, residual clay that is the product of weathering. He does mention that kaolinization may on occasion be caused by other processes, but he stresses that the hydrous aluminum silicates in clay are produced chiefly by the decomposition of feldspar. It is only within the last few years that the formation of kaolin by other processes such as hydrothermal activity has been seriously considered.

Jacobs (1926) depends on the residual weathering of feldspar to account for the East Monkton deposit by simply saying that the kaolin lies under a quartzite capping, contains fragments of feldspar, and is probably residual. He also discusses the origin of the Bennington kaolin by stating that feldspar fragments, much kaolinized, and quartz are associated with the clay. Jacobs (1926, p. 209) goes on to say that "One must conclude, therefore, that the feldspathic rocks, whose alteration has resulted in the formation of kaolin, lie below the clay deposits." He does admit that he was not able to find any feldspathic facies in the quartzite which occurs in the mountains directly to the east of the kaolin deposits, and concluded that the kaolin deposit must be a transported one whose origin was to the north.

Burt (1927) describes the Bennington kaolin in detail and attributes its origin to a normal weathering process during the Tertiary period, the parent rocks being the Precambrian gneisses of the area, and to a lesser extent the feldspathic and argillaceous members of the quartzite. He does not feel that they are transported, and he gives petrographic evidence of the gneissic parentage of most of the kaolin. It is interesting to note, however, that no feldspars are present in the upper part of the deposits (Allen and Johns, 1960) or in samples down to a drill hole depth of 155 feet. Also, a sample containing a vein of milky quartz (Allen and Johns, 1960) shows that the angular quartz has kaolinite etched on three surfaces. This same association of milky quartz veins to the kaolin is quite evident in the lower ore body

at East Monkton, suggesting contemporaneous formation of the kaolin and quartz as a result of hydrothermal activity.

Dana (1898) records the contemporary formation of residual clays from the feldspathic members of the quartzites in Berkshire County, Massachusetts, a few miles south of Bennington. Burt (1930) also writes of the development of clay from feldspathic and argillaceous beds of the quartzite in the silica quarries in Cheshire County, Massachusetts, about 20 miles south of Bennington.

In Connecticut, residual deposits of kaolin have been described at West Cornwall. The deposit is described by Ries (1927) as being unique in that it is derived from a somewhat steeply dipping feldspathic quartzite, and within the deposit occur "unweathered" beds of quartzite. Borings at this locality by a wash drill show kaolin at a depth of over 100 feet. The major structure appears to be an anticline, its limbs dipping east and west and its crest plunging gently to the south. The kaolinized zone is sandwiched between hard, massive Poughquag quartztite layers. The kaolin is also said to have the appearance of the original quartzite and shows numerous quartz grains which have not been decomposed. The origin of the deposit is attributed to a quartzite layer containing a high percentage of feldspar that has been converted to a mass of kaolin and quartz by the action of "rain water" working its way down through fractures and converting the feldspar to kaolin.

All of these kaolin deposits resemble the East Monkton deposit, yet there are definite indications that the Monkton deposit is not residual kaolin formed by the surface weathering of a feldspathic rock. That deposits of this extent and depth are solely the result of the decomposition of feldspar (which in many cases is not present) must be questioned. The writer can only base his results on observations made at the East Monkton deposit, yet the other western New England deposits appear in many ways geologically similar.

Modern theories concerning the formation of kaolin by hydrothermal activity are of interest, and may be the key to the study of the kaolin deposits in western New England. The hydrothermal and pneumatolytic origin of kaolinite was recognized as long ago as 1819 when a group of German scientists noted that kaolin deposits occurred at the top of a granite stock between converging hematite veins. Also, the presence of fluorspar was noted in some kaolin deposits, and from this it was concluded that kaolinization had been brought about by hydrofluoric acid vapors. The German scientists became strong advocates of the idea that kaolin is not formed by weathering but by the action of thermal waters or pneumatolytic processes.

The pneumatolytic theory was studied by J. H. Collins (1887), who strongly supported the theory that

the kaolins of the Cornwall District of England were of pneumatolytic origin. In the Cornwall District are found some of the deepest known kaolin deposits in the world, occurring in a granite traversed by tin veins; they have been worked to a depth of several hundred feet. Collins sought to show that the kaolin was formed by the action of fluoric vapors on the granite, and attempted to prove experimentally that this was possible by exposing feldspar to the action of hydrofluoric acid. According to his reports, the feldspar was converted to a hydrated silicate of alumina, mixed with a soluble fluoride of potassium, while pure silica was deposited on the sides of the test tube. When examined microscopically, the artificial clay produced resembled washed kaolin.

Since the early experimental work of Collins, many laboratory experiments have been conducted in an attempt to artificially establish the conditions for the formation of kaolin. Many of these experiments have been successful; however, more pertinent to the theory of this report are the formation of kaolin deposits under natural conditions. These conditions and results may not be strictly similar to the formation of the Monkton deposits, yet the overall process appears to be similar.

R. A. Daly (1928) reports on the feldspathization of quartzite within the Bushveld igneous complex of the Transvaal. The metamorphism of the sandstone has resulted in an impressive enlargement of the quartz grains. This increase in grain size is thought to have taken place in the originally more porous layers, where connate water was most abundant. Steam or "water-gas" was forced through the porous layers of the heated sediments, the resulting solution and recrystallization of the quartz leading to the increase in grain size. The action, then, would be somewhat analogous to that in a common coarse vein of quartz. The most important process, however, is the feldspathization of the quartzite, especially where it is in contact with the granophyre or coarse granite. One specimen has about 17 percent by weight of soda-rich orthoclase and oligoclase-albite in equal proportions, while another specimen contained an even higher percentage of feldspar, making up approximately half of the rock. It is noteworthy that even though much of the quartzite has undergone feldspathization, its original cross-bedding is well preserved in the outcrops. Daly feels that the genetic problem is particularly important on account of the fact that the large-scale alteration of the Bushveld quartzites seems clearly to be the same as that discussed in relation to the "red rocks" of Minnesota and other areas, where there definitely has been a feldspathization and development of graphic texture in quartzite through the influence of invading granophyric and granitic magma.

Quirke (1927) made a study of the Lorraine Quartzite in Sudbury, Ontario, and found a similar situation where the feldspathization of the quartzite has taken place. The conversion seems to have involved the replacement of large quantities of quartz by feldspar. There has been a feldspathization of the quartzite by the process of assimilation within the magmatic invasions and beyond the contact of the intrusives. Again, it is interesting to note that the original structural attitude of the sediments has been preserved in spite of the profound mineralogical alteration.

In connection with the same line of reasoning, Bailey and Tyler (1960) have come up with a theory relative to the formation of the clay minerals associated with the Lake Superior iron ores. They have found that kaolinite can be formed readily over a wide range of temperatures, either by hydrothermal synthesis from the oxides, by reaction of gels, or by alteration of feldspars, but both their synthesis data and evidence provided in field relationships for similar clays elsewhere in the world, suggest that the clay mineral assemblage in the Michigan iron ores is primarily the result of hydrothermal activity.

C. M. Riley (1959, p. 185) discusses an occurrence of mercury on the slopes of the Sierra Morena at Almaden, Spain. The ore occurs in highly folded and faulted rocks of Silurian age, and the sequence of slates and quartzite layers have a nearly vertical attitude and were partially replaced by cinnabar. The theory here is that the solutions, probably derived from the quartz-porphyry intrusion, chose the quartzite layers because of a higher permeability and favorable chemical nature, or both. The significance of the deposit lies in the fact that the solution first introduced sericite, with the ore minerals later replacing the sericite and quartz.

In the writer's opinion, the best description of a kaolin deposit that resembles the one at East Monkton is that of the occurrence at St. Remi in Amherst County, Quebec. Here a deposit of kaolin is associated with Precambrian quartzite in a zone of fracturing, and according to Wilson (1919), is of hydrothermal origin. These deposits, like those at East Monkton, are peculiar in that they are not associated with highly feldspathic rocks but with quartzite. The kaolin has been deposited *in situ* along fracture and fault planes, but more important is the fact that relationships between the kaolin and the quartzite definitely show that much of the deposit is a result of the replacement of the quartzite wall rock by kaolin. Wilson feels that it is reasonable to assume that, if the deposits have been derived from a deep-seated source, they have presumably been formed by the alteration of feldspar contained in granite occurring along the lower margin of the fracture zone, and have been carried upwards and deposited in the upper part of the zone by ascending thermal waters.

Osborne (1935) discusses the kaolin deposit at St. Remi and considers that the quartzite was originally feldspathic, and that the feldspars were replaced by

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hydrothermal solutions coming from the granites of the region. There seems to be agreement that the deposit is a result of hydrothermal activity; however, Osborne's theory that the feldspar already was in the quartzite and later replaced, is questionable. A great amount of feldspar would be required to form a deposit as extensive as the St. Remi one, which has been stressed by Wilson and will be discussed later on in this report when replacement evidence is cited. At any rate, it would seem more reasonable to assume that at both St. Remi and East Monkton, the replacement process involved a great deal more than the few feldspar grains found in the quartzites.

Allen and Johns (1960) had x-ray diffraction patterns made of the St. Remi kaolin and found many books of micaceous plates of kaolinite present. They also found hydrous mica (sericite), quartz, and a few rounded zircon grains. They feel that the presence of kaolinite suggests that the replacement process took place at a temperature below that which dickite forms. Just as is the case at East Monkton, the redistribution of the kaolinite and quartz, and the known extension of the deposit to a depth exceeding 150 feet would favor the hypothesis of replacement by warm magmatic solutions rather than by surface solutions associated with normal weathering processes.

Hypogene Origin

HYDROTHERMAL REPLACEMENT

Hydrothermal alteration is defined in the *Glossary of Geology* (1957, p. 143) as follows: "Those phase changes resulting from the interaction of hydrothermal stage fluids (hydrothermal solutions) with pre-existing solid phases, such as the kaolinization of feldspars, etc. . . . Also used to cover changes in rocks brought about by the addition or removal of materials through the medium of hydrothermal fluids."

The definition covers both processes of hydrothermal activity, which, it would seem, has resulted in the formation of kaolin in the Cheshire Quartzite at East Monkton. There is conclusive evidence that the cementing medium of secondary silica in the quartzite has been replaced by kaolin. The quartzite layers so attacked have not been highly metamorphosed and exhibit the original bedding. Intercalated with these quartzite layers are thin layers of a schistose material. The alteration of these thin layers of graphitic, sericite schist to kaolin requires the method cited in the other part of the definition of hydrothermal alteration, namely, that there has been an interaction of hydrothermal solutions with a solid phase. Hydrothermal action is extremely varied, and here it is apparent that the results of this action depended upon the kind of host rock involved. Furthermore, such abundant changes in mineralogy and in chemical composition can

take place only when relatively large amounts of solutions are present. The altered quartzites thus produced, are proof that large amounts of solutions moved through the rocks, to say nothing of the kaolin deposited.

Physical changes brought about by hydrothermal alteration are varied. According to Schwartz (1959), altered rocks are generally more porous and permeable, and the alteration is found to be a result of the penetrative powers of solution rather than diffusion. Textural changes brought about by hydrothermal alteration often result in a disseminated mass of very fine-grained minerals with a definite decrease in grain size. This is the situation within the quartzite layers at East Monkton, since the replacement of the fine-grained silica cement by kaolin produces an extreme change in grain size.

Fractures play an important part in hydrothermal alteration since permeability is necessary for the introduction of the hydrothermal solutions. According to Schwartz (1959), a genetic relationship exists between alteration and fracturing, and the control of fracturing in non-calcareous rocks is generally thought to be physical and structural rather than chemical. Intense fracturing and brecciation certainly is conspicuous in the East Monkton area, and it becomes evident that hydrothermal alteration and associated processes have had an important effect on the preparation of the rock for kaolin enrichment by the development of porosity and permeability, in addition to introducing the necessary minerals.

Schwartz (1959) states that it is generally accepted that the minerals formed during hydrothermal action depend upon four main conditions: 1. composition of the original minerals and rocks, 2. composition of the invading solution, 3. temperature, and 4. pressure. Time is also important in the phase relationships, since it is evident that equilibrium is not commonly reached during hydrothermal processes, and the stage at which action ceases is therefore important.

The number of minerals formed is large, particularly in the group of clay minerals. Kaolinite was the first clay mineral to which a hydrothermal origin was assigned, and now most clay can be said to have been formed as a result of hydrothermal activity at some place or time (Schwartz, 1959). Schwartz also states that the common minerals formed as alteration products are: sericite, quartz, chlorite, sulfides, epidote, zoisite, clinozoisite, alunite, calcite or other carbonates such as ankerite, and the clay minerals. There appear to be many differences of opinion on this point, but generally quartz, sericite and clay minerals are characteristic of the intermediate and acid rocks. Also, shaly rocks are commonly characterized by sericite and dolomite (ankerite).

It seems that quartz is an important mineral in the

hydrothermal alteration process, and silicification can be intense. The amount of silica released by the alteration of feldspar to sericite or kaolin is likely to be fine grained and difficult to identify (Schwartz, 1959). Quartz is actually introduced by hydrothermal solutions, generally occurring as veinlets such as those so evident in the undisturbed section of the Bushey pit in the East Monkton deposit.

Sericite is one of the most characteristic minerals of hydrothermally altered rocks. In igneous rocks it replaces feldspar in the early stage, but later in the process it replaces ferromagnesian minerals, commonly with chlorite as an intermediate product. Schwartz (1959) states that quartz can also be attacked by the sericitization process.

Of the less common minerals, tourmaline deserves comment since it occurs in deposits that are typically hydrothermal. Tourmaline is abundant in greisen developed under so-called pneumatolytic conditions, but some geologists believe that the liquid phase is more important than the gas phase in such alterations. Deposits in Bolivia have tourmaline in association with kaolinite, chlorite and muscovite. In Quebec, black tourmaline occurs as vein fillings and as extensive replacement in schists and granodiorite in deposits classified as hydrothermal. At East Monkton some authigenetic tourmaline occurs with the kaolinite and sericite.

It is evident that most of the kaolin at East Monkton has resulted from the replacement of the silica cement in the quartzite. It would be convenient if the cementing medium was once a carbonate, but the writer believes that the cement which the kaolin has replaced was the same as that in the unaltered quartzite, to wit, a fine-grained secondary silica.

Quartz is generally thought to be resistant to most kinds of alteration, but it was noted by Schwartz (1956) that in cases of severe argillitic alteration it is attacked around the periphery of large grains, which is also the case at East Monkton. Ries (1927) concedes that quartz, although apparently resistant, is not left untouched. He has found that in petrographic studies of various siliceous rocks, replaced silica grains and authigenetic siliceous minerals commonly occur in the same strata. The suggestion is that the silica dissolved during replacement provides a significant quantity of that precipitated authigenetically. The writer believes this to be the case at East Monkton, along with the fact that hydrothermal alumina-bearing solutions reacted with much of the replaced silica to form the kaolin, but it appears that the conditions causing this type of replacement are not well understood.

What caused the silica to become soluble is a difficult question to answer. Studies indicate that the solubility of quartz increases rapidly with an increase in pH ranges above pH 9, but in the geologically common range from pH 5 to pH 9, the solubility is nearly constant. Since the alkalinity of water under natural conditions does not generally rise above pH 9, it seems probable that the replacement of the silica is caused by factors other than pH variations alone. Phase relationships such as high temperature and pressure resulting from deep burial may possibly promote this replacement. The writer feels that it is a result of hydrothermal alumina solutions reacting with the secondary silica cement, and since the quartz cement was fine grained, much of it was completely dissolved, leaving the primary grains as grit or sand in the kaolin. Ries (1927) reports on a deposit of indianite near Huron, Lawrence County, Indiana, within the Pottsville Sandstone, in which he favors the theory that the white clay was formed by the replacement of the quartz pebbles in the Pottsville Sandstone. The theory is that the pyrite of the Chester Shale would, by contact with the underground waters, be decomposed and yield sulphuric acid, which would attack the alumina of the associated shales and form an aluminum sulphate. As the unconformity between the Chester Shale and the Pottsville Sandstone is a zone of weakness, and the sandstone of the Pottsville is very porous, a good path is formed for the circulating waters, hence bringing the sulphate solutions in contact with the quartz pebbles to form indianite. Ries states that aluminum sulphate will alter silica, although he admits that the exact reaction by which the hydrous aluminum silicate is formed, cannot be stated. We are faced with just such a problem in the East Monkton kaolin deposit where there is phyllitic material, quartz, and indications of solution, but no evidence as to how the reaction forming the hydrous aluminum silicate took place.

There is much evidence, especially in the recent excavation in the Bushey pit, to indicate that large masses of kaolin have been deposited by replacement. The silica cement in the quartzite layers adjacent to the planes of faulting and fracturing and in the altered layers of phyllitic material, has been carried away, or was reacted upon by circulating waters, and kaolin deposited in its place.

The following observations offer evidence that these masses of kaolin have resulted from replacement:

1. The surfaces of the quartzite beds are channeled and contain voids in which the kaolin was deposited.

2. Beds of unaltered quartzite remain essentially in their original dipping attitude throughout the kaolin deposits.

3. In many places the bedded and cross-bedded structure of the replaced kaolinic quartzite is preserved within the kaolin body itself.

4. The large primary quartz grains in the quartzite have a marked horizontal elongation and lineation which are preserved in the kaolin, even where the

kaolin constitutes over half of the material.

5. Most of the quartzite next to the phyllitic layers (which have been altered to sericite and kaolin) is completely devoid of silica cement and consists of a friable mass of oriented primary quartz grains.

6. Thin sections of the kaolinic quartzite and casts of this material definitely show solution cavities and accompanying masses of kaolin.

7. Milky opaline quartz veins are associated with the kaolin and kaolinic quartzite.

Hydrothermal Solutions and Kaolin Formation

The products of hydrothermal alteration in the outer portions of the earth's crust are formed by a process which follows the crystallization of igneous masses. Clay minerals formed by this hypogene process result from the action of gases, vapors, or solutions that originate at depth and find their way up through the overlying rocks. According to Kerr (1955), most of the elements of the clay minerals are contributed by the invaded rocks. The chief materials removed from these crustal rocks are alumina, silica, alkali or alkaline earth metals, and iron. These materials are transformed into clay minerals at temperatures ranging from below 100 degrees centigrade to about 450 degrees centigrade in an environment that may be acid, neutral or alkaline, depending upon the pH of the invaded rocks and the acidity of the vapors from the magma. The different mineralogical and chemical responses within the wall rock are not dependent on a drastic change in the hydrothermal fluid itself, nor on the periodicity of its operation, but on continuously varying conditions of physiochemical environment within the wall rock outward from the source.

The belief that the more volatile constituents of magmas, as they leave the crystallizing masses, are acid in reaction, though they may change their characteristics as they move on, has become fairly well established. Gruner (1944) has found that these acid solutions are inadequate to produce ore deposits and that it is immaterial whether the acidity is produced by halogens or the SO_4 radical, since the pH of a solution is the most important factor. What is most important is that the solutions do exist, and that certain hydrothermal minerals have been formed by them as can be demonstrated by numerous laboratory experiments.

Gruner (1944) feels that such hydrothermal solutions exist and that clay minerals can be formed by them. To demonstrate this he selected potash and soda feldspars and subjected them to certain laboratory conditions. With a temperature range of 300 to 400 degrees centigrade and the acidity of the solution 0.1 normal, he found that kaolinite, pyrophyllite, sericite and boehmite are formed in acid solutions. He also found that kaolinite will form from feldspars and is stable below

350 degrees centigrade regardless of the potassium ion concentration, providing the ratio of alumina to silica is about 1 to 1. This means that additional and easily available alumina has to be in the system.

Armstrong (1940) treated samples of microcline and albite in the laboratory and found that all of the constituents of the minerals diffused through a dialyzer. This was interpreted as evidence that all of the constituents were present in solution in the ionic state, and that clay minerals may form, at least in part, by ionic reactions as well as colloidal reactions. Over 50 percent of the alkalies were removed from the feldspars by dialysis. X-ray photographs showed that substantial amounts of the minerals were undecomposed and that no detectable new mineral had been formed. However, after treatment of the decomposed minerals in water at 300 degrees centigrade, x-ray photographs displayed a new line indicating the formation of quartz and other new lines suggesting the formation of kaolinite.

Morey and Ingerson (1937) found that feldspar first breaks up into primary decomposition products, some of which recombine to form kaolin. An important factor is that they also show that feldspar composition is not necessary to form kaolin; it is only necessary to have a mineral that can furnish the necessary decomposition products. They conclude that kaolinite can form solely by the reaction of alumina and silica in neutral alkali-free solutions, or in acidic alkali-containing solutions below 400 degrees centigrade.

The composition of hydrothermal solutions under natural conditions presents a difficult problem, but in most cases such waters are thought to be acid and begin with carrying chlorine, sulphur, carbon dioxide and/or silica. The composition of the solutions then must change as reactions take place with the host rock, and in the case of silicate rocks the solutions would become alkaline as a consequence of such reactions. The alkaline constituents would then probably be transported outward by the solutions, and the alkalinity of the solutions would persist only so long as alkalies or alkaline earths were being released by the breakdown of the parent rock. As the action of the acid water proceeded, therefore, the acid-alkaline front would move outward with the alkaline earths and alkalies. It must be taken into consideration, however, that hydrothermal solutions may not always be initially acid. The warm water could have originally been alkaline and rich in potassium which became neutral and finally acid with progressive cooling. This sequence of reactions would favor the formation of kaolin and appears to be applicable to the East Monkton deposits.

Kaolinite, then, may form from any aluminum silicate constituents if the environment is acid and the temperature moderate. According to Bundy (1958), acid conditions, low temperature, and low pressure

for the formation of the kaolin group of minerals, and kaolinite will form below 350 degrees centigrade with minimum silica and alumina concentrations regardless the concentration of potassium. It is interesting to note that Bundy finds that when calcium is present in the environment, the formation of kaolin is retarded.

Recently the Chinese have conducted a great deal of research in an attempt to establish the relationship between hydrothermal solutions and clay minerals. Juan, Wang and Sun (1958) discuss the hydrothermal alteration of andesite on the island of Taiwan in connection with the ore deposits there, which are products of post-igneous activity of an andesite magma. The important fact is that an argillization zone has been created and is represented by a kind of soft, kaolinite-quartzite-sericite rock. This is much the same condition as that found at East Monkton. Evidently the plagioclase in the original andesite has been altered to this argillaceous material. They feel that the argillization stage is characterized more by subtraction rather than addition. Considerable loss was shown in lime, silica, iron alkalies, phosphorous oxide and magnesia. Addition was only in alumina and possible titania. An important point here is that they find that oxidation may produce sufficient sulphuric acid to neutralize and make normally alkaline water acidic.

Pei-Yuan (1958) also studied the clay of hydrothermal origin as derived from the andesites of Taiwan. He found that acid conditions favor the formation of kaolin minerals. The alkalies and alkaline earths in the decomposed minerals are soluble in the acid solutions and are removed from the altered rock, leaving alumina and silica to form kaolin minerals. Wherever the acid is strong, with a pH value of about 4 or even lower, the water will readily dissolve even alumina, but silica is only slightly soluble. The importance is that when sulphate-bearing solutions percolate through the ground, in a variable environment, they react with the andesite material and alter these rocks into kaolinic clays by replacement. Another point of interest in the Pei-Yuan report is that during the argillic alteration an excess of silica was released and this was responsible for the entrance of opaline silica in the clay. Other research workers such as MacDonald (1944) have described the actions of solutions believed to be weak in carbonic, sulfurous and sulfuric acid, and have found that opal and kaolinite are developed. This relationship of opal and kaolinite in other hydrothermal situations is of interest here since thin, opaline veins are found in the kaolinic quartzite at East Monkton (specimen K 27, number 2).

The abundance of the hydrothermal mineral sericite in the East Monkton kaolin deposits obviously plays some sort of role in the kaolin-forming process. According to Lindgren (1915), the agencies which produce mineral deposits are not capable of developing kaolin from the aluminum silicates of the rocks; on the other hand, when sericite is exposed to weak sulphuric acid waters in the oxidized zone, a leaking of the potash takes place and the sericite is converted to kaolin. The fact that sericite is generally recognized as being an intermediate stage toward ultimate kaolinization is also supported by Sand (1956). That sericite is the most abundant and characteristic of the hydrothermal minerals, appears to be universally accepted.

Contrary to the generally accepted theory that both silica and hydrous aluminum silicates remain behind in the alteration process, Leonard (1927) finds that only silica is the principal remainder, the major portion of the alumina being removed along with the more soluble constituents. Any gain of alumina in the solution can be explained by the supposition that the waters contained sulphuric acid, since only such thermal waters are known to dissolve alumina in large quantities.

It appears that the effects of hydrothermal solutions depend upon too many variables to make definite predictions as to exact mineral formation. The discussion in this report only scratches the surface of the material published on the subject, and the writer feels he is not qualified to go into the subject any further. The means by which such changes take place in the quartzite layers are not known and no satisfactory physical-chemical explanation seems available. The object of this report is to present evidence that the kaolin formation is a result of activities from a deep-seated source, and not to explain the exact nature of the solutions and the resulting reactions within the country rock that produced the kaolin.

Since the quartzite belt in which Monkton deposits are found, lies between the Mount Holly Complex and the Barber Hill syenitic body, it is probable that the zone of fracturing and faulting, in which the kaolin is found, intersects the Mount Holly Complex and bodies of syenite or granite at depth. It is possible, therefore, that thermal solutions ascending along the fracture and fault planes might obtain the necessary constituents and transport them upward, reacting with the Cheshire Quartzite and depositing the kaolin. At any rate, it is quite apparent that hydrothermal solutions have altered the phyllitic layer within the quartzite to kaolin, and also replaced a great deal of the secondary silica cement in certain quartzite layers to form a kaolinic quartzite.

SUMMARY AND CONCLUSIONS

The kaolin deposit located in the town of Monkton, Vermont, occurs at the western base of the Green Mountain Range in a zone of fracturing and faulting. The metamorphosed host sediments are Lower Cambrian in age, and consist mostly of quartzite containing relatively thin layers of a graphitic, quartz sericite

schist. No known igneous bodies occur in the immediate vicinity of the kaolin deposits, although they are a prominent feature of the regional geology. The proximity of igneous bodies to the kaolin deposits at depth is highly probable but purely suppositional.

The kaolin occurs within the fractured zone as narrow layers occupying the beds of phyllitic material, as narrow veins following fracture and joint planes, as a matrix enclosing broken fragments of quartzite, and as replacement deposits. Large quantities of silica have been carried away in solution and the kaolin deposited has preserved the original structures of the quartzite.

The occurrence of the kaolin in a fracture zone in which feldspar or other aluminum silicates are almost entirely lacking, indicates that the kaolin has not been developed *in situ*, but has been carried into the fracture zone from an extraneous source. The deposits were derived from a deep-seated source, as evidence presented in the report indicates; they have most probably been formed by the alteration of feldspar within the Mount Holly Complex and in the syenites or granites supposedly occurring in the lower parts of the fracture zone. The constituents have been transported upward by ascending thermal waters with reaction and replacement taking place in the upper part of the fracture zone.

Certain features exhibited by the kaolin deposits have a definite bearing on the conclusions.

1. The kaolin occurs in a zone of fracturing and faulting in the Cheshire Quartzite. This association permits the ascent of kaolinizing vapors and solutions.

2. The principal kaolin deposits so far discovered occur in quartzite and therefore the kaolin has not been developed *in situ*, but has been transported into its present position.

3. The relationship of the kaolin to the texture of the kaolinic quartzite shows that the kaolin has been deposited, in part, by the replacement of the quartzite wall rock.

4. There is a common association of kaolin with hydrothermal minerals such as sericite, opal, and authigenetic tourmaline. Sericite is abundant, although it is not generally a product of weathering. Where authigenetic tourmaline occurs in the quartzite it generally lies on the surface of bedding planes, adjacent to milky quartz veins or, associated with other openings where circulating waters had penetrated.

5. Many of the voids in certain horizons of the kaolinic quartzite contain authigenetic feldspar (mostly microcline). This feldspar does not show the decomposition effects of kaolinization although kaolin occurs throughout the formation.

6. The kaolin deposit extends to greater depths (100 feet and more) than could possibly result from surface weathering. Also, layers of massive quartzite within the formation act as a protective cap rock.

7. Milky veins of quartz and thin veinlets of opaline silica appear to be clouded with kaolinite, indicating their contemporaneous formation.

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