



STRATIGRAPHY AND STRUCTURAL RELATIONS
OF THE CARBONATE ROCKS IN THE DOVER PLAINS, N.Y.,
QUADRANGLE

by

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I. ABSTRACT

The Dover Plains quadrangle in the Southern Taconic area of southeastern New York is underlain by Precambrian gneiss, Cheshire quartzite, Stockbridge dolomite and limestone, and the Hudson River schist all presumably of Cambro-Ordovician age. This study is concerned with the structure, stratigraphy, and metamorphism of the Stockbridge formation and the structure and lithology associated with the schist-marble contacts.

The Cheshire quartzite has been subdivided into 3 units. Dale's reconnaissance subdivision (1923) of the Stockbridge formation into "calcitic" and "dolomitic" sequences has been verified and the sequences have been further subdivided into a total of 11 units. A correlation with the Cambro-Ordovician limestones and dolomites of western Vermont and Massachusetts is suggested.

The Stockbridge formation overlies the Cheshire quartzite which rests unconformably on the Precambrian gneiss in the northeastern part of the quadrangle. The Stockbridge forms an eastward-dipping isoclinally folded sequence which is in contact with the Hudson River schist to the west; in addition, the formation is gently folded about an east-west axis. The major period of deformation is later than the major period of metamorphism as indicated by rotated diopside crystalloblasts and deformed east-west trending pegmatites.

The rock units above and below the schist-marble contacts are consistently similar from Amenia, New York south to

Pawling, New York and east to Bulls Bridge, Connecticut, and vary in mineralogy with increasing metamorphic grade.

The impure dolomitic rocks contain plagioclase, tremolite, actinolite, and diopside indicating a low to moderate thermal rank of metamorphism. Metamorphism generally increases from north to south and is not parallel with the strike of foliation in the carbonate rocks.

II. INTRODUCTION

1. Location and Regional Geologic Setting

The Dover Plains quadrangle (latitude $41^{\circ}37'30''$ to $41^{\circ}45'$, longitude $73^{\circ}30'$ to $73^{\circ}37'30''$) is in Dutchess County, New York and parts of Litchfield and Fairfield Counties, Connecticut, about 70 miles north of New York City and 20 miles east of Poughkeepsie (Fig. 1-a). The rock formations in the quadrangle are a part of the Precambrian and Paleozoic sequence which extends from southern Quebec to Georgia (Fig. 1-b). In the northeastern portion of the quadrangle East Mountain, underlain by Precambrian gneiss and Cambrian Cheshire quartzite, is the southern most extension of the Taconic Range. The remainder of the quadrangle is underlain by the crystalline Stockbridge limestone (or Wappinger limestone) of Cambro-Ordovician age and the Ordovician Hudson River schist which grades eastward into the slate and shale of the Hudson River lowlands. The intensity of metamorphism of the pelitic rocks increases from northwest to southeast exhibiting the following mineral facies (Barth, 1936):

- 1) muscovite slate facies, 2) kyanite schist facies,
- 3) sillimanite gneiss facies.

Nearly all the land forms are controlled by bedrock. Schist and gneiss underlie the higher hills, and carbonate rocks underlie the valleys. The quadrangle is divided physiographically by the prominent valleys of the Swamp and Tenmile Rivers. Many slopes exceed 40° , and most of them are the slopes of East and West Mountains bordering the Harlem Valley

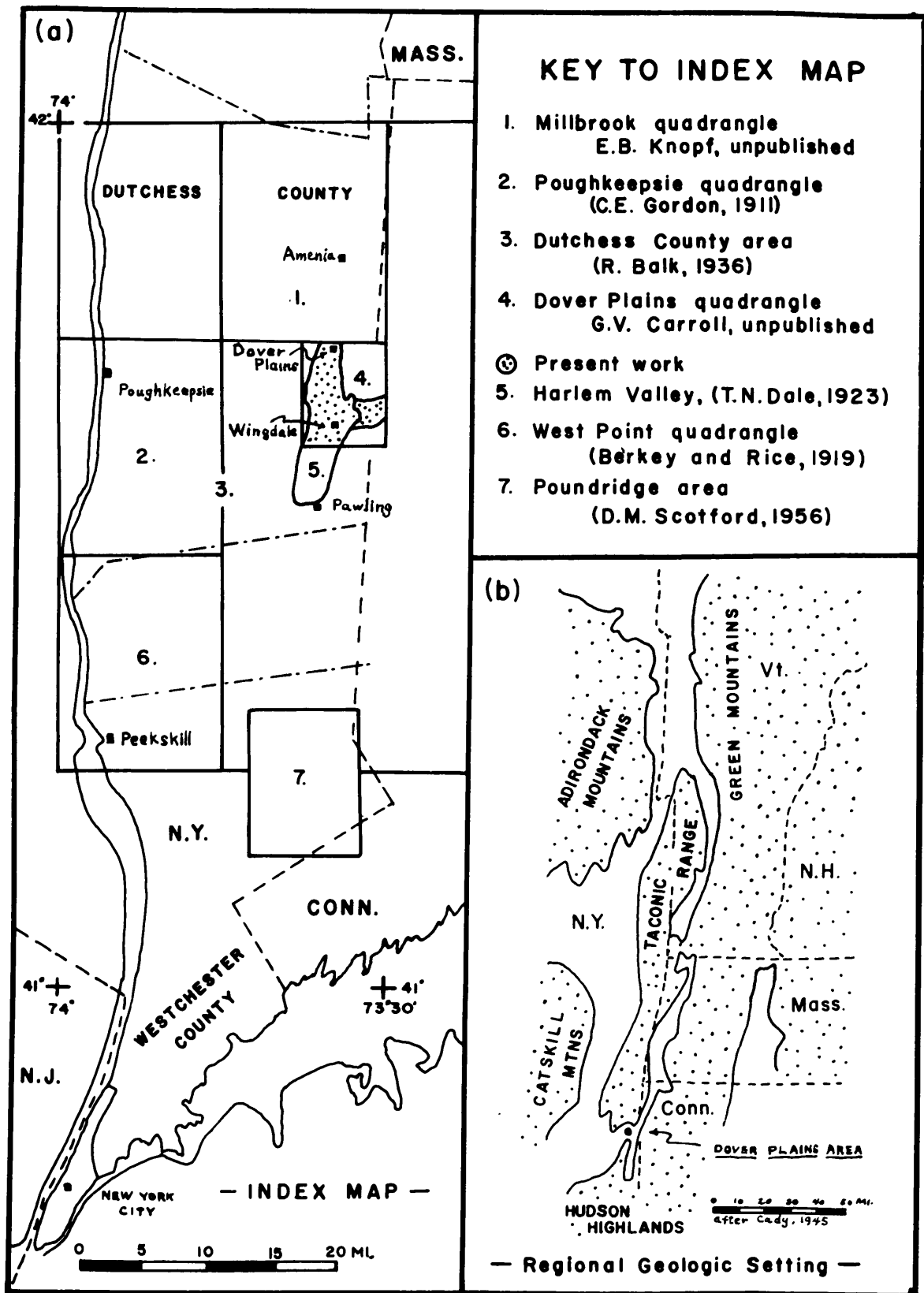


Figure 1.- Index map and regional geologic setting.

which extends north-south through the quadrangle. The total relief ranges from 1,414 feet on East Mountain to less than 370 feet south of Dover Plains.

The Harlem Valley which is a continuation of the Stockbridge formation and is the area of this study, The area, covering about 15 square miles, is readily accessible by automobile, being traversed by New York Route 22 in a north-south direction and Route 55 in an east-west direction. Poorly sorted glacial debris has been deposited in the valley, leaving about one third of the bedrock exposed. Nearly one-fifth of the valley is covered by swamp. Drainage is dominantly controlled by bedrock; the small, steep hills are underlain by schist and quartzite and the lowlands are underlain by nearly pure carbonate rocks.

2. Previous Work

The Taconic Range is directly adjacent, across the strike, to the area underlain by the slightly metamorphosed Hudson River pelite and limestone of eastern New York. The rocks of the Taconic Range are schist, marble, quartzite, and gneiss. It was concluded by Emmons (1842) and others that the rocks of the Taconic Range were metamorphosed before the Hudson River rocks were deposited, and were therefore much older. Mather (1843) observed that "the Taconic rocks are the same age as those of the Champlain division but modified by metamorphic agency..." Subsequent work by J.D. Dana (1879, 1887), C.D. Walcott (1888), and W.B. Dwight (1890)

established the Cambro-Ordovician age of the quartzite-limestone-pelite sequence in Dutchess and Westchester Counties and correlated it directly with the similar sequence in western Massachusetts and Vermont.

The early stratigraphic work in Dutchess County was extended and summarized by Gordon (1911) and Knopf (1927) who correlated the fauna Ollenelus thompsoni, Prosaukia, Ellesmeroceras, and Lecanospira with the respective lower and upper Cambrian and lower Ordovician.

T.N. Dale (1923) mapped the carbonate rocks of the Stockbridge-Harlem Valley from northern Massachusetts through Connecticut into eastern Dutchess County subdividing them into upper calcitic and lower dolomitic sequences. South of Dutchess County the age of the carbonate rocks is still in question. They have been mapped as Cambro-Ordovician, Grenville, and "doubtful" ages according to degree of metamorphism by Berkey and Rice (1918) in the West Point quadrangle. Bucher (1951) interpreted the same rocks near Peekskill as Cambro-Ordovician based on a gneiss-marble contact where "rounded cystoid fragments and boulders of metamorphic and igneous rocks" were found in the crystalline marble. Prucha (1955) and Scotford (1956), working in northeastern Westchester County, concluded that the Fordham gneiss, Inwood marble, and Manhattan schist are a conformable sequence either of entirely Precambrian or Paleozoic age and cannot be correlated with the Precambrian Highland gneiss and the sedimentary sequence of Dutchess County. Scotford

recognized the necessity for a detailed stratigraphic section of the carbonate rocks and correlation of recognizable units with the Cambro-Ordovician sequence of western Vermont and Massachusetts but did not subdivide the Inwood formation.

The regional structure is also unsettled. Knopf (1927) recognized that the axes of folding are not concordant with the direction of increasing metamorphism and that a "zone of intensely deformed and mylonitized rocks along the western edge of the belt of highly metamorphic schists 'suggest' the surface emergence of imbricate thrust plates..." Dana (1885) and Agar (1932, 1935) recognized a similar disparity between strike of foliation and increase of metamorphic grade. Knopf (1954), in a preliminary fabric analysis northeast of the Dover Plains quadrangle, indicated at least three and possibly four distinct deformations. The detailed work of Robert Balk (1936) showed no evidence of long distance movements along low angle thrust faults, and that the deformation of the sedimentary formations is associated with normal faults and thrust faults dipping eastward at angles between 35° and 80° . The relation between deformation and metamorphism proposed by Balk and Barth (1936) is discussed below. Balk correlated the Lowerre-Inwood-Manhattan sequence with the Dutchess County sedimentary rocks.

Attempts have been made to subdivide the carbonate rocks of the Dover Plains area by Dale (1923), Balk (1936), and Carroll (1953). Dale was successful in mapping two sequences in a reconnaissance fashion, as noted above; Balk rejected

the practicality of stratigraphic work in the area because of the intense deformation and metamorphism. Carroll subdivided the rocks into an eastern "lower" Stockbridge and a western "upper" Stockbridge including some dolomite and calcdolomite in the "upper" sequence. He did not trace the contact between the quartzite and schist in the eastern part of the quadrangle or south into the Pawling 7½ minute quadrangle. Thus, no detailed subdivision of the Stockbridge has been made in the Dover Plains area; consequently, the gross structure of the valley and relation between schist and marble is not clear. Subdivision of the metamorphosed carbonate rocks in the Dover Plains area may lead to correlation with the fossiliferous Cambro-Ordovician limestone and dolomite sequence in western Vermont and Massachusetts; the subdivision may aid in subdividing the Inwood marble to the south in Westchester County and possible correlation of the Inwood with the Stockbridge in Dutchess County.

3. Purpose and Method of Study

This study is concerned with the structure, stratigraphy, and metamorphism of the Stockbridge formation in the Dover Plains quadrangle. The following specific problems were studied:

- 1) Subdivision of the Stockbridge into mappable units.
- 2) Analysis of the gross structure of the rocks between East and West Mountains and the relation of minor structural features to the major structure.

- 3) Structural and mineralogic characteristics of the metamorphosed contacts between the Hudson River and Stockbridge formations.

About two months of summer field work were carried out during 1958 and 1959. Laboratory work and preparation of the manuscript occupied parts of the 1958-1959 and 1959-1960 academic years.

The U.S. Geological Survey 7½ minute quadrangle (scales: 1:31,680 and 1:24,000) of Dover Plains, New York-Connecticut and photostat enlargements (scale 1:12,000) were used as base maps along with serial photographs (scale: 1:15,840) from the New York Conservation Department. Laboratory techniques included thin section preparation, mineral identification by oil immersion, and $\text{Cu}(\text{NO}_3)_2$ staining of polished sections to distinguish calcite and dolomite (Rodgers, 1940).

4. Acknowledgements

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III. STRATIGRAPHY OF THE CARBONATE ROCKS

1. General Statement

Subdivision of the sedimentary rocks in the Dover Plains area is hampered by the complex structure, the scarcity of outcrop due to glacial cover, and variations in metamorphism over short distances. In the valley it is rarely possible to follow the outcrop of a single unit more than 500 feet along the strike. To date no fossils have been found in any sedimentary rocks in the quadrangle. Deformation and metamorphism have been sufficient to destroy fossils in the pure limestones or dolomites; the more resistant chert layers and quartzites remain possibilities.

The distinction made by Dale (1923) is correct and well defined in the field. The contact may be distorted or smeared due to plastic flow but it can be recognized by differences in grain size and reaction with acid where the rocks are highly metamorphosed; or by color, grain size, and reaction with acid in lower grade rocks. The writer was unable to trace Carroll's (1953) contact between upper and lower Stockbridge in the field.

Further subdivision of the carbonate rocks appears to be possible. The following modification of Dale's subdivision is used:

<u>Dale</u>		<u>Present</u>
Hudson River-Berkshire schist	Sequence IV	-----
Stockbridge formation - upper	Sequence III	Units 3-A,B,C,D
-do- - lower	Sequence II	Units 2-A, etc.
Cheshire Quartzite	Sequence I	upper, middle and lower

2. Cheshire Quartzite

The Cheshire quartzite is not a part of this study but in hoping to find a quartzite-marble contact, it was possible to identify three subdivisions in the quartzite (locality 43, Plate I - 2½ miles southeast of Dover Plains on East Mountain):

Upper - 50 to 70 feet of impure (dolomitic?) quartzite which weathers as a less competent horizon than those underlying it. It is a thin-bedded pure white quartzite with layers of impure, partly schistose quartzite.

Middle - 60 to 70 feet of thin-bedded white quartzite interbedded with tourmaline-bearing gray schist (Fig. 2).

Lower - In contact with the Precambrian gneiss is a 5 to 10 feet impure transition zone which is overlain by 150 to 200 feet of uniform, smooth salmon-weathering vireous red and white quartzite.

3. Stockbridge Formation - Sequence II

Introduction - Sequence II overlies the Cheshire quartzite and is generally a pure, fine- to medium-grained massive dolomite interbedded with considerable thicknesses of quartzite, calcdolomite, dolomitic sandstone, thin schist beds, and chert. The non-carbonate layers are more resistant and weather differentially as raised ribs and ridges. The pure dolomitic rocks in the lower units do not react with HCl but the silica-rich layers and the upper units of dolomite show a spotty reaction to acid. In some zones diopside, tremolite, feldspar and actinolite are conspicuous minerals.



Figure 2.- Thin-bedded gray schist and white quartzite of the middle unit (1-B) of the Cheshire quartzite. Between Dover Plains and Wingdale on East Mountain - Locality 43.

Subdivision of this sequence in the present work is unclear and perhaps inaccurate because of the possibility of repetition in isoclinal folding. The apparent stratigraphy is given for several localities followed by a tentative summary of the overall Sequence II stratigraphy. The convention used is overlying units, listed first with a reversed numbering sequence.

The carbonate rocks are recrystallized but will not be called "dolomitic marbles". The thicknesses measured are only approximate and do not account for changes caused by folding.

Bain's Corner - The Bain's Corner area includes the outcrops south of Bain's Corner between the Tenmile River and East Mountain, north of the $\frac{1}{2}$ mile east-west bend in the river. The western outcrops are dominantly granular-weathering, massive sparkling-gray dolomite with red and gray quartzite and a few beds of white dolomite and calcareous dolomite. The central area contains more white dolomite, thick sections of sparkling-gray dolomite with tremolite and actinolite, buff- and gray-weathering fine grained gray dolomite with conspicuous schistose partings, and many beds of dolomitic sandstone and quartzite. The eastern outcrops are largely resistant pure white dolomite, dolomite with raised siliceous ridges, and some black- and brown-weathering beds of gray quartzite. The units from west to east are:

- 7) 100 feet of buff- and gray-weathering coarse-grained massive gray and white calcareous dolomite which

reacts with HCl. Some units contain pyrite, mica, and small clusters of calcite; and are thinly banded (loc. 10).

- 6) Massive red and gray quartzites below thick massive units of gray dolomite described below as localities 8 and 9.
- 5) 60 to 100 feet of nearly pure sparkling gray dolomite forming rounded, granular- and platy-weathering outcrops. The lower units are 5 to 8 feet of similar gray dolomite abundant in radiating clusters of tremolite and actinolite, 5 to 10 feet of gray dolomite with only tremolite, and 15 to 20 feet of white dolomite. The white dolomite is more resistant than the gray, is coarse grained, and weathers to a smooth buff surface.
- 4) 20 to 30 feet of quartzite and sandy dolomite underlain by 10 to 15 feet of hard massive white dolomite with a characteristic green coating beneath the weathered surface. These overlie 60 to 70 feet of sparkling gray dolomite with thin schistose partings.
- 3) 20 to 40 feet of quartzites and dolomitic sandstone.
- 2) 250 to 300 feet of sandy and schistose dolomite which ranges from a fine-grained pure white dolomite with a low percentage of siliceous ribs to a fine grained buff- and pink-weathering light gray or white dolomite containing 20 to 40 percent siliceous and schistose ribs. Gray quartzites in the buff-

weathering beds are 1 to 12 inches thick; schistose ribs are more common in the upper units of gray dolomite. The ribs are spaced a fraction of an inch to a foot apart; pyrite in the highly siliceous layers causes them to weather dark brown or brownish-red.

Often the ribs are not pure silica but very thinly laminated dolomitic sandstone where dolomite and silica have reacted during metamorphism to form limesilicate minerals. This recrystallized unit then responds to deformation in the same way that a unit of pure quartz responds.

- 1) 20 to 30 feet of massive, medium- to coarse-crystalline pure white dolomite generally free of siliceous or schistose partings (loc. 3 and 6).

Locality 8 - Quartzite-dolomite sequence is well exposed in an abandoned road cut and is a good example of unit 6 described above.

- 4) 110 feet of massive, thick bedded, medium- to coarse-crystalline gray dolomite.
- 3) 5 feet of nearly pure gray quartzite in 3-5 inch beds separated by thin layers of gray dolomite.
- 2) 20 feet of black schistose dolomite and fine-grained dark gray dolomite with 2 feet of hard, black cherty layers at the top and schistose partings in the middle. The lower 10 feet contains many siliceous partings.

- 1) 25 feet of red and gray quartzite. The upper beds are hard, massive light gray and dark gray quartzite 3 to 5 feet thick overlying a 2 foot bed of gray dolomite. The lower beds are 4 feet of thin-bedded red and white massive quartzite overlying a bed of gray quartzite. The quartzite contains minor calcite and pyrite; it is extremely resistant and forms a major ridge. None of the quartzites resemble any units of the Cheshire. This unit has not been successfully traced down the valley but it does not appear to pinch out as if the occurrence were a lens.

Locality 9 - Another characteristic lithologic unit is a thick, massive granular- and platy-weathering dark gray dolomite with large resistant clusters of quartz crystals containing calcite and some plagioclase (?). These clusters weather out as a conspicuous debris on the outcrop.

Cricket Hill - The rock units south of elevation 483, north of elevation 554, and between East Mountain and the tracks of the New York Central Railroad are a transition between the dolomite-quartzite sequence described above and Sequence III. The units are traced from locality 27 to locality 31 and are characterized by a large variety of rock types:

- 6) Dark gray calcdolomite ("calcdolomite" is a mixed rock containing both calcite and dolomite) containing clusters of phlogopite, very coarse crystals of calcite, and diopside crystals which stand out on a

weathered surface. Outcrops weather to a buff-gray chamois coating. The calcdolomite is interbedded with granular-weathering fine-grained dark gray dolomite and 3-inch beds of limesilicate. The uppermost units are in contact with Sequence III at locality 32.

- 5) Light- to bluish-gray calcdolomite, limestone, dolomite, 1 to 5 inch beds of black chert, thin beds of gray quartzite, and fragments or crystals of diopside, plagioclase, and quartz. Some beds of gray dolomite appear to be a conglomerate with thin fractured bands of calcite. Pyrite is the source of orange and buff staining. Associated with the thin quartzites are spongy-weathering layers of limesilicate (diopside and plagioclase ?). Beds of dark bluish-gray nodular dolomite with thin white calcite stringers occur in the lower parts of this zone.
- 4) Sequence of dolomite, black chert, and thin banded red and gray quartzites which vary from 1 to 5 inches thick. Black chert appears in the upper part of the zone.
- 3) 100 to 300 feet of white and light gray fine-grained massive dolomite with one or two 8-inch beds of gray quartzite. Thickness of units increases downsection to beds nearly 3 feet thick.
- 2) Thick beds of gray and white dolomite with tiny sheared quartz blebs and thin fractured layers of

phlogopite-calcite schist and black chert. This zone at locality 29 is a sequence of 1-to 3-inch resistant ribs of red- and black-weathering calcite marble containing pyrite and phlogopite; the fresh surface is grayish-green and pink.

- 1) Sequence of dolomitic quartzite, gray quartzite, and smooth-weathering fine-grained gray and white dolomite with inclusions of calcite and limesilicate.

South Dover - Outcrops of dolomitic quartzite, quartzite, and gray dolomite occur in a similar sequence to the Bain's Corner section:

- 2) Medium-grained gray dolomite interbedded with thick dolomitic quartzite and gray quartzite overlying gray dolomite with resistant 6-inch beds of gray quartzite (loc. 39).
- 1) 150 to 200 feet of nearly pure gray dolomite with occasional thin siliceous partings. The lower 40 to 50 feet is a darker gray, more resistant, and is interbedded with thin ribs of dolomitic quartzite and black chert.

Ellis Pond - Reconnaissance east of Ellis Pond, with an attempt to outline the units overlying the Cheshire quartzite, gave the following section:

- 3) 200 to 300 feet of sparkling gray dolomite with occasional thick beds of quartzite and dolomitic quartzite grading downward into 6 to 8 inch beds of

quartzite. The lower half of the zone is nearly pure gray dolomite without schistose or siliceous impurities (loc. 37). In the lowest 10 feet are several 3-foot horizons of gray tremolitic dolomite; the rod-like tremolite crystals occur up to one inch in length.

- 2) 25 feet of quartzite and a resistant horizon of dark gray dolomite containing tiny nodules of diopside or plagioclase (loc. 36). A similar horizon can be found associated with quartzites at localities 1 and 7. A stained polished section from locality 1 shows dense, fine-grained dark gray dolomite surrounding small white inclusions of limesilicate and very thin stringers of calcite. This is a possible marker bed for tracing the lower units of Sequence II.
- 1) 140 feet of medium-grained white dolomite with limesilicate, calcite, and micaceous partings. It grades upward into 100 feet of gray dolomite with thin black shaly partings. The white dolomite at locality 38 is 300 feet east of the Cheshire quartzite.

Bulls Bridge - The sequence at Bulls Bridge is highly deformed and metamorphosed, and the structure is uncertain. Outcrops are in the Housatonic River bed and a continuous section is exposed for nearly a mile downstream from the dam. A fault separates the Sequence III-schist units from the dolomites and is not described here. From locality 42 south

the sequence is:

- 5) Coarse-grained granular-weathering calcareous gray dolomite grading into pure dolomite which is interbedded with smooth-weathering, thin-banded thick gray quartzites separated by 5 to 30 feet of dolomite; dolomitic sandstone is rare. The quartzite is 3 to 24 inches thick and highly contorted, boudinaged, and sheared. Well-formed 1 to 3 inch diopside crystals are scattered throughout the dolomite.
- 4) 200 feet of coarse-grained partly calcareous sparkling gray dolomite separated every 3/4 to 6 inches by thin schistose partings. The entire section is free from quartzite layers, and the only impurities in the dolomite are large diopside crystalloblasts and clusters of radiating tremolite. This is in contact with fine-grained gray dolomite downstream.
- 3) Red-orange- and buff-weathering thick dolomitic quartzites, pure quartzites, and fine-grained gray dolomite. Frequently the 3 to 6 inch-bedded dolomite is separated by one inch layers of black chert. The tough quartzites are intensely sheared and pinched; they are occasionally separated by a thick horizon of a green limesilicate minerals. The larger siliceous horizons are separated by thick massive beds of gray dolomite containing diopside and tremolite. The dolomite weathers easily and the

quartzite protrudes above the river bed as highly resistant ridges.

- 2) 30 to 40 feet of extremely coarse-grained calcite marble and thick beds of sparkling light gray dolomite containing diopside, tremolite, siliceous and schistose beds, and quartz-calcite pods. The white calcite marble weathers to a coarse granular surface; the layer increases in thickness from 2 to 24 inches to several feet thick in an abandoned quarry downstream.
- 1) One-half mile south of the bridge at least one-quarter mile of the river bed is a sequence of fine-grained thin-banded pure white dolomite, gray dolomite, schistose partings and thin ribs of salmon-weathering gray quartzite. The layers are intensely sheared, and stretched into thin ribs. Compositional banding is thinner and has a higher percentage of siliceous and schistose partings upstream.

Nellie Hill - The transition between Sequence III and the lower zones of Sequence II is similar to the first two units of the Cricket Hill section:

- 2) In contact with Sequence III (loc. 13) is a smooth-weathering fine-grained light gray dolomite with quartz blebs and thin layers of chert. East of locality 13 the dolomite and calcdolomite is thinly laminated, medium- to coarse-grained, and contains small rounded quartz grains. Limesilicate minerals

(particularly diopside) are rarely developed in this unit in contrast with the same unit of the Cricket Hill sequence at locality 32.

- 1) Light to dark gray fine-grained dolomite interbedded with calcdolomite, 1 to 5 inch beds of black chert, and thin beds of gray calcite and dolomitic sandstone. (localities 11 and 12). The upper units of this zone are a conspicuous fine-grained dark gray dolomite and tightly folded schistose partings. Clusters of plagioclase, quartz, and calcite occur in the dolomite; pyrite is the source of orange and buff staining. This zone is similar to zone 5 of Cricket Hill and also occurs at localities 2 and 25. The thin bedding of the quartzite and the occurrence of black chert, gray dolomite, and calcdolomite in this particular combination distinguish this unit from Bain's Corner units 2, 3, 4, 5, and 6.

Sherman Hill - The rock units in this vicinity can be divided into two zones:

- 2) Medium- to coarse-grained grayish-green, pink, gray, and white banded calcdolomite with thin gray schistose partings and $\frac{1}{2}$ to 1 inch layers of brownish-gray chert. Phlogopite and pyrite are common; thin quartz blebs which appear to be fractured remnants of thin sandy layers are conspicuous on a weathered surface. Locality 24 is typical of the grayish-green calcdolomite.

- 1) Medium- to coarse-grained thinly laminated massive white gray dolomite and calcdolomite with disseminated pyrite, phlogopite, and quartz blebs (loc. 22). Brown calcite-phlogopite schist occurs at locality 20.

Summary - Sequence II can be divided, from the top of the sequence down, into several distinct units:

Unit 2-G - Medium to light gray dolomite and calcdolomite with thin layers of black chert, clusters of coarse calcite, quartz, and well-formed diopside crystals. Where in contact with Sequence III the dolomite fine grained and a layer of chert occurs 6 inches from the contact. Typical localities: 32, 13, Figures 3 and 4.

Unit 2-F - Light to dark bluish-gray dolomite and calcdolomite, thin beds of black chert, gray quartzite, dolomitic sandstone, and crystals of quartz or diopside. Typical localities: 2, 11, 25, 26, 27.

Unit 2-E - Thin- to thick-bedded white, gray grayish-green, and pink dolomite, limestone, and calcdolomite with minor amounts of gray quartzite, thin schistose partings, pyrite, phlogopite, and clusters of calcite. Overall thickness of units increases upsection. This unit is not well-defined at present. Typical localities: 29 and 42.

Unit 2-D - Thick beds of massive coarse-grained gray and dark gray dolomite with thin layers of black chert and large clusters of quartz crystals. Typical localities: 9, 37,

and 39.

Unit 2-C - 25 feet of gray quartzite and red and white laminated dolomitic quartzite mark the upper portion of this unit. Underlying the thick quartzites are 6- to 8-inch beds of light gray quartzite interbedded with thick beds of sparkling gray and white dolomite. Typical localities: 8, 37, 39, and 42, Figure 5.

Unit 2-B - The dolomite of Unit 2-C grades downward into a thick sequence of nearly pure coarse-grained sparkling gray dolomite with several horizons of dolomite containing radiating clusters of tremolite and actinolite. At higher metamorphic grade diopside occurs rather than tremolite. Typical localities: 4, 37, 39, and 42, Figure 6.

Unit 2-A - Thick beds of red-orange- and buff-weathering dolomitic quartzite and thin beds of gray quartzite and black chert interbedded with fine-grained gray dolomite. The lower portion of the unit consists fine-grained buff- and pink-weathering white dolomite with thin gray quartzite ribs and schistose partings. Where the impure white dolomite grades into the upper beds of dolomitic quartzite the beds are closely spaced and have a higher percentage of siliceous impurities. Quartz grains and schistose partings occur in the basal portion where the dolomite is relatively pure. Typical localities: 5, 6, 38, 42, and 44.

4. Stockbridge Formation - Sequence III

Introduction - Sequence III overlies the calcdolomite and dolomite of the Lower Stockbridge and is typically a granular-weathering coarse-crystalline black, orange, white, and blue-gray limestone. It is in direct contact with the Hudson River formation and has a consistent lithology where exposed. The limestone sequence comprises about 15 percent of the total thickness of the Stockbridge formation in the Dover Plains area, and is easily weathered so that outcrops are rarely exposed. It can be subdivided into four distinguishable units which can be traced from areas of low-grade to high-grade metamorphism. The thickness of the sequence is 200 to 300 feet at the Nellie Hill locality south of Dover Plains.

Nellie Hill - The large outcrop on Route 22 is an excellent, nearly complete section of Sequence III. The section is overturned and dips 70 degrees eastward. A schist-marble contact is 1000 feet north (loc. 14) and a contact with Sequence II is 400 feet east (loc. 13). The rock units are recrystallized limestone (calcite marble) and occur in four distinct zones:

- 4) 35 feet of brown-weathering black limestone with intensely deformed stringers and clusters of calcite and quartz. A stained polished section shows the limestone to be fine-grained with small flakes of mica and tiny black particles between the calcite grains.



Figure 3.- Steeply-dipping grayish green dolomite, calc-dolomite, and schistose dolomite of Unit 2-G. Note weathered surface in contrast to fresh surface. The shallow-dipping north-south joints normal to the compositional banding is presumably associated with the Sherman Hill anticline. Two miles south of Dover Plains on Route 22 - Locality 24.



Figure 4.- Differentially weathered fragments of sheared quartz layers parallel to compositional banding. Hammer handle is in the plane of east-west joint and normal to the compositional banding. Thin bands of calcite weather out differentially to give a smoothly ribbed surface. Unit 2-G - 800 feet northwest of locality 24.

3) 110 feet of thick-bedded gray limestone and dolomite containing horizons of a coarse quartz-calcite schist. Large, well-formed calcite crystals, pyrite, garnet, and tourmaline are characteristic of the schist. Bedding is thinner and smaller quartz ^{grains} are common in the upper part of the zone.

2) 45+ feet of medium-grained, thinly laminated massive light olive-gray and bright orange limestone with thin micaceous partings, stringers of calcite, and quartz knots. It weathers to a thinly ribbed or smooth, shiny surface with calcite weathered out in $\frac{1}{2}$ - to $\frac{1}{4}$ -inch ragged bands. When deeply weathered the orange limestone is a sugary mass of tiny orange-stained prismatic calcite crystals. Coarse-grained blue-gray and orange limestone is interbedded with the finer-grained limestone, and it dominated the middle part of the zone as smooth-weathering massive beds.

One bed is composed of alternating layers of blue-gray limestone and thin bands which appear to be an intraformational conglomerate. The "conglomerate" bands contain small tabular fragments of black chert, bluish-gray limestone, orange limestone, and rounded quartz grains; the fragmentation does not resemble any of the minor structures found in highly deformed carbonate rocks. Several horizons have undulating (not folded) contacts which suggest scour-and-fill



Figure 5.- Sheared and stretched quartzite, dolomitic quartzite, and gray dolomite of Unit 2-C (?) in the Housatonic River bed south of Bulls Bridge. To the left of the resistant siliceous rocks is the readily-weathered gray dolomite. Locality 42.

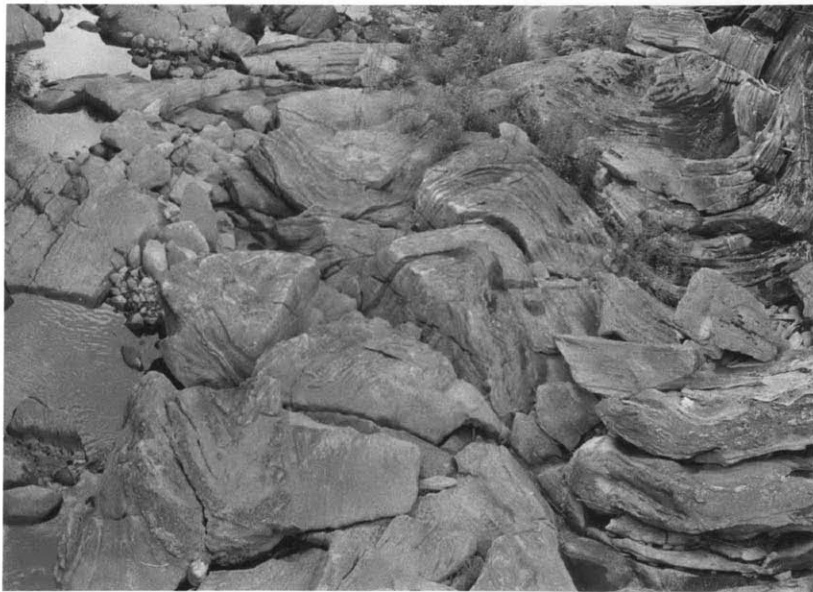


Figure 6.- Tight south-plunging folds in the thin-bedded, diopside rich coarse-grained dolomite horizon of Unit 2-C. Looking south from the bridge over the Housatonic River at locality 42. Differentially weathered siliceous impurities are visible in the foreground.

channels in the limestone.

- 1) In contact with Sequence II is a 10 to 20 foot zone of uniform, dense lead-gray limestone which weathers to a massive granular surface. Several thin beds of white limestone occur in this zone near the overlying orange limestone.

Wingdale - The limestone crops out 1 mile northwest of Wingdale forming a continuous but highly contorted section of Sequence III with contacts at both the Hudson River formation (loc. 34) and Sequence II (loc. 32). Four subdivisions are observed:

- 4) Coarse-crystalline blue-gray and white banded micaceous limestone with quartz and calcite stringers and radiating clusters of tremolite. The beds are similar to but more intensely deformed than unit 4 of Nellie Hill. Near the contact with the Hudson River formation the beds are more schistose and resistant to weathering.
- 3) Coarse-crystalline orange-, white-, and gray-weathering gray and blue-gray limestone with conspicuous raised black micaceous or cherty stringers and 1 mm. crystals of biotite. Very coarse-grained pods of calcite, muscovite, and quartz are common.
- 2) Thick-bedded, very coarse crystalline orange and white limestone with small raised reticulations of limesilicate. At locality 34 the orange limestone is in contact with fine-grained dolomite which may

be part of Unit 2-G or a bed of dolomite interbedded with the limestone. The outcrops weather to a hard, gleaming granular surface. Nearly perfect 1 to 2 mm. prismatic crystals oriented parallel to the foliation characterize both units 1 and 2 in this area.

- 1) In contact with white dolomite of Unit 2-G (loc. 32) is a very coarse crystalline granular-weathering white limestone. Prismatic crystals of calcite are surrounded by a dark gray pigment and weather to a black mottled surface. The fine-grained dolomite at the contact contains diopside, stringers of chert, and coarse pods of calcite.

Summary - The calcitic limestone mapped by Dale (1923, pl.IV) can be divided into four units:

Unit 3-D - Brown-weathering fine-grained black limestone with swirled stringers and clusters of calcite and quartz. Near the contact with the Hudson River schist the beds are coarser grained, thinly banded, and somewhat argillaceous, Figures 7 and 8.

Unit 3-C - Thick-bedded, often thinly laminated, blue-gray and gray limestone and dolomite interbedded with a coarse quartz-calcite schist, Figure 9.

Unit 3-B - Medium-to coarse-grained granular-weathering light olive-gray and orange limestone with knots and stringers of calcite, quartz, and black chert, Figure 10.

Unit 3-A - Uniform granular-weathering dense lead-gray limestone and several thin beds of white limestone.



Figure 7.- Schistose marble at the contact between the Hudson River schist and the upper Stockbridge. Looking north in the direction of foliation at locality 34 west of Wingdale.

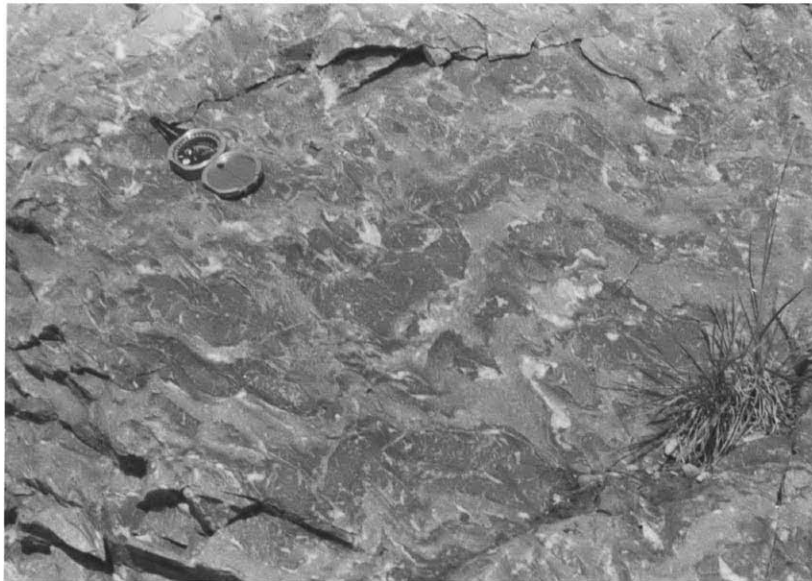


Figure 8.- Black limestone with highly deformed stringers and pods of calcite and quartz from Unit 3-D. Outcrop on Route 22 $\frac{1}{2}$ mile south of Dover Plains and east of locality 13.



Figure 9.- Blue-gray limestone and black argillaceous chert with stretched layers of gray chert weathering differentially on the surface. Calcite-filled east-west fracture cuts the compositional banding and is relatively undeformed. Unit 3-C at locality 34 west of Wingdale.

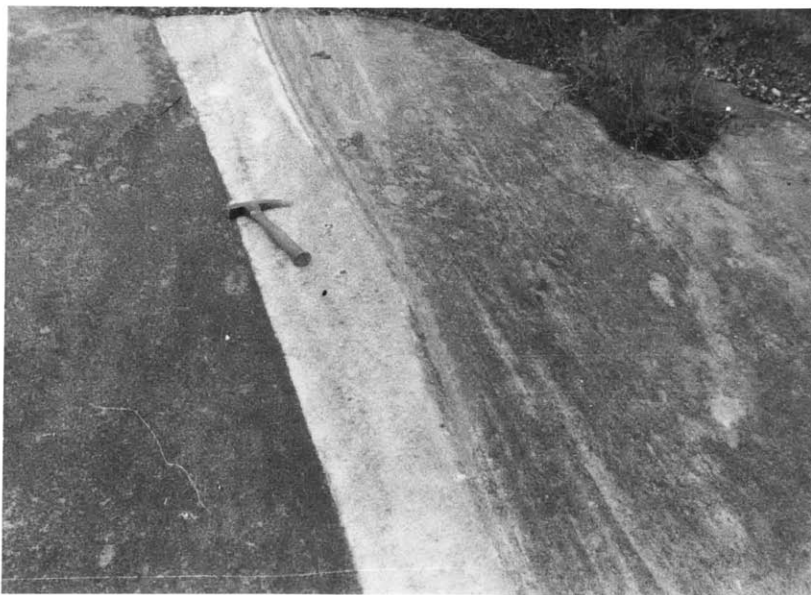


Figure 10.- Coarse-crystalline orange and white limestone of Unit 3-B. Hammer rests on bed of pure white limestone. Looking northeast at locality 34 west of Wingdale.

Typical localities are 13, 32, and the Bulls Bridge schist-marble contact. The four horizons described undergo several characteristic changes with increasing metamorphism: development of limesilicates and biotite, and the formation of large prismatic calcite crystals.

5. Suggested Correlation of Units

Despite the intense deformation and metamorphism in this area, the subdivisions of the Stockbridge formation outlined above are remarkably consistent from Bulls Bridge and Wingdale to Dover Plains. The relative order of the units and structural relations are reasonably clear for the localities discussed. Figure 11 is a suggested correlation chart comparing the Dover Plains subdivisions with those of Knopf (1946, 1959), Cady (1945), and Herz (1958) in the Millbrook quadrangle, New York; west-central Vermont; and the Cheshire quadrangle, Massachusetts respectively. The correlation proposed here is tentative since it is deficient in the following features: 1) fossil correlation, 2) unknown thickness of the units, and 3) definitions of the boundaries of the subdivisions. The formations described by Cady have been traced south into the Rutland area, Vermont (Brace, 1953) and into the Bennington quadrangle, Vermont (MacFayden, 1956). Herz described a similar sequence in the Stockbridge Valley (Cheshire quadrangle, Mass.). The highly metamorphosed units at the latitude of Wingdale may provide criteria for distinguishing subdivisions in the Inwood marble of Westchester County to the south.

		DUTCHESS COUNTY Knopf (1946)	DOVER PLAINS AREA This Report	WEST-CENTRAL VT. Cady (1945)	CHESHIRE, MASS. Herz (1958)		
ORDOVICIAN	Middle	Trenton shale	Hudson River fm.	Hortonville slate	Berkshire schist		
		Trenton-Black R. ls.	Stockbridge Group	Glens Falls ls.			
				Unit 3-D		Orwell ls.	
				Unit 3-C		Middlebury ls.	
				Unit 3-B		Beldens fm.	
		Unit 3-A		Crown Point ls.			
	Lower	Copake ls.	Unit 2-G	Bridport dol.	Stockbridge Group		
		Rochdale ls.	Unit 2-F	Bascom fm.		Bascom fm.	
		Halcyon Lake fm.	Unit 2-E	Cutting dol.		Shelburne marble	Shelburne marble
				Shelburne marble			
Briarcliff dol.		Unit 2-D	Clarendon dol. Springs	Clarendon dol. Springs			
Pine Plains fm.	Unit 2-C	Danby fm.	Danby (?) fm.				
CAMBRIAN	Middle						
		Stissing dol. (5 members)	Unit 2-B	Winooski dol.	Kitchen Brook dol.		
	Unit 2-A		Monkton qtzite.				
			Dunham dol.				
	Lower	Poughquag qtzite.	Cheshire qtzite.	Cheshire qtzite.	Cheshire qtzite.		
1-C			Cheshire qtzite.				
1-B			"Mendon Series" "Mt. Holly Series"	Dalton fm.			
		1-A					

Figure 11. - Suggested stratigraphic correlation of the Dover Plains area with areas to the north

IV. SCHIST-MARBLE CONTACTS

1. General Statement

Contacts between the Hudson River and Stockbridge formations have been investigated to determine stratigraphic relations of the two rock types and the effect of increased metamorphic grade on the contact. Those contacts sampled and studied crop out near Amenia and Wassaic (Amenia 7½ minute quadrangle), Dover Plains, Wingdale, Webatuck, Bulls Bridge (all in Dover Plains quadrangle), and Pawling (Pawling 7½ minute quadrangle).

At each contact calcite limestone is "gradational" into graphitic shale; graphite and thin argillaceous layers occur in the limestone within 2-25 feet of the contact. The transition is not "gradual" but a horizon of 50 percent argillaceous limestone overlies nearby pure thin bedded, coarse, black limestone. The graphitic shale is in direct contact with the transition horizon and contains little or no calcite and it does not react with HCl. All the contacts are highly deformed so that sampling is possible from more than one outcrop; the thickness of the transition horizon is indeterminate due to the folding. Thin sections have been made from Amenia, Wassaic, Webatuck, and Bulls Bridge contacts.

2. Contact Localities

Amenia (roadcut on Route 22, ½ mile south of Amenia, New York).

The carbonate horizon at the contact is a thinly bedded coarse grained black and light gray recrystallized limestone

with contorted stringers of coarse-grained calcite and quartz; the groundmass contains minor amounts of quartz, chlorite, and graphite. The overlying argillaceous unit is a grayish green graphitic chlorite-biotite schist; small flecks of graphite parallel the foliation; biotite replacing chlorite retains the graphite inclusions. Rotated biotite crystals are observed with graphitic layers displaced from original orientation. The contact dip is nearly vertical.

Wassaic (roadcut on Route 22, 1½ miles north of Wassaic, New York).

Below the shallow dipping contact is a thinly laminated, coarse, recrystallized dark gray limestone with minor pyrite and crenulated micaceous laminations with graphite paralleling foliation. Above the contact is a "greasy", grayish green, graphitic chlorite-biotite schist tightly crenulated normal to the planes of compositional banding.

Dover Plains (½ mile southwest of Dover Plains; Plate I, locality 15).

The contact is a series of tight, south plunging folds which are expressed by topographic highs (schist) and corresponding depressions (marble) and dips steeply to the east. Below the contact is a thinly laminated light gray calcite marble with micaceous parting and thinly laminated black calcite marble with attenuated pods of quartz and muscovite.

Seven Wells ($\frac{1}{2}$ mile south of Dover Plains; localities 14 and 16).

This contact is similar in both outcrops; the schist overlies the marble in a small, north plunging anticline.

Three units occur at the contact:

- 1) Medium-grained thinly-laminated black crystalline marble with stringers and large pods of white calcite which are more intensely folded than the similar pods and stringers of the Dover Plains contact. 500 feet north of locality 14 is a similar black marble.
- 2) Two inches of sheared, limonite-stained coarse-crystalline gray and white quartz and muscovite, with small limonite-filled cavities of weathered sulfide (?) minerals. This zone is tightly interfolded with schist and marble.
- 3) Rusty-weathering, dense, fine-grained black graphitic biotite schist.

Wingdale ($1\frac{1}{2}$ miles northwest of Wingdale; localities 33, 34, and 35).

The contact dip varies from 20 degrees to vertical depending on location on the folds.

A thinly laminated blue-gray schistose marble is in contact with a hard black graphitic biotite schist. The marble contains pods and stringers of coarse white calcite and quartz in which tremolite is developed; the transition horizon is about 2 to 5 feet thick (Fig. 7).

Webatuck (1 3/4 miles east of Webatuck, off Route 55; locality 40).

Contact crops out in a pasture and is covered with drift and deeply weathered. Thin-banded blue-gray calcite marble similar to Wingdale contact forms the walls of a gravel pit 1/4 mile east (loc. 41).

The carbonate horizon is a sugary-weathering pale gray calcite marble with small crystals of phlogopite. A zone of diopside, biotite, hornblende (?), phlogopite, pyrite, calcite and quartz separates the marble from the overlying biotite - sillimanite schist. The schist is a dense dark gray graphitic rock; sillimanite replaces biotite and garnet. The garnets are corroded and rotated but retain the original graphitic laminations; "S" structure of graphite in the garnet indicates a 60 degree rotation. Sillimanite is parallel to the foliation while biotite has no preferred orientation. Both schist and marble contain pyrite and graphite along carbonate and silicate grain boundaries. Under reflected light, the graphite appears to surround the pyrite crystals.

Bulls Bridge (1/4 mile west of Bulls Bridge, Connecticut on the west shore of a large island in the Housatonic River; locality 42).

Here the rock units above and below the vertical schist-marble contact can be divided into six types:

- 1) Thin-layered yellow and gray coarse crystalline calcite marble with feldspar, pyrite, phlogopite, and diopside impurities (100 feet exposed). Light

gray micaceous marble similar to Dover Plains and Wingdale contacts.

- 2) Calcite-biotite schist transition zone, 3 inches to 2 feet thick with minor amounts of quartz, diopside, graphite, and pyrite.
- 3) Intensely sheared 3 inch zone of dark gray and white quartz coated with iron oxide.
- 4) 2-4 inch zone of 90 percent pale green diopside with minor microcline, plagioclase (An₇₀), and pyrite along diopside-feldspar boundaries. Diopside replaces both microcline and plagioclase.
- 5) Dense, fine-grained black graphitic biotite schist with small crystals of quartz, mica and calcite replacing large crystals of diopside. Pyrite and graphite occur along grain boundaries with graphite partially surrounding the pyrite crystals; sillimanite is present but not abundant.
- 6) Biotite-sillimanite schist with large pods and stringers of quartz (30-40 feet exposed).

Pawling (3/4 mile west of Pawling, New York at elevation 479 on north embankment of Route 55).

A second outcrop is on north-eastern slope of hill 620, 30 yards south off the highway; the contact is in a tight isoclinal fold. The dip of both contacts is nearly vertical. The rock types are similar to the Seven Wells and Bulls Bridge contacts; the following assemblages occur at the contact:

- 1) Coarse-grained, thin-layered yellow and gray calcite marble with phlogopite, diopside, and pyrite as minor constituents. Some laminations are of very coarse calcite or black micaceous calcite nearly identical with the black and white banded marble of the Wingdale and Bulls Bridge contacts.
- 2) Medium to dark gray thinly laminated crystalline marble with numerous white calcite stringers and micaceous laminations.
- 3) Sheared zone of iron oxide-stained gray and white quartz crystals with small clusters of muscovite and large limonite clusters. The muscovite and limonite from weathered sulfide (?) minerals suggests that the zone may not be related to original sedimentation. [Note that ore bodies of limonite occur in the schist near the schist-marble contacts in western Massachusetts and Connecticut and southeastern New York - Mather (1842), Balk (1936, p.695), and Herz, (1958).]
- 4) Dense black biotite-sillimanite schist with tiny deformed garnet crystals; similar to schist at Webatuck contact.

3. Summary

The thinly banded coarse-grained black limestone and dense black graphitic schist occur at nearly all the contacts sampled. Except for degree of metamorphism and deformation,

limestone or schist sample cannot be distinguished in hand specimen from one locality to the next. The contacts are conformable with the local structure even where the iron-stained quartz zone occurs. The gradation zone is never the same thickness at any two contacts but has similar lithology at all the contacts.

The Bulls Bridge diopside zone is unique and suggests an attempt to establish local equilibrium in the presence of a chemical potential gradient across the contact between silicate and carbonate phase assemblages, (cf. Thompson, 1959, pp. 430-434). The silicate impurities in the marble at this contact are similar in quantity to the impurities found at other lower grade contacts; phlogopite is the dominant mica rather than chlority or biotite. Similarly, the silicate assemblage (schist) contains little or no calcite and is very similar to the black schist occurring at the other contacts. From this evidence it is suggested that chemical equilibrium at the contact has been established by reaction of schist and marble at the contact forming a nearly monomineralic equilibrium phase of diopside between carbonate and silicate. There is no evidence that chemical equilibrium has been established by "silica metasomatism" of the carbonate rocks at the contact or "calcium or carbonate metasomatism" of the schist. The contacts between schist, diopside, and marble are sharp; any silicates occurring in the marble can be accounted for at other contacts. Chemical analyses of the major constituents of the separate assemblages at the contact are

presently being made to verify the mineralogic observations.

Finally, present observations indicate the individual outcrop contacts between schist and marble are stratigraphically conformable; lithologies of both carbonate and pelitic rocks substantiate this conclusion for several grades of metamorphism. Whether or not the gross regional contacts of schist and marble are stratigraphically conformable remains an open question, e.g., Balk (.1936.) mapped the contact between schist and marble between Wassaic and Dover Furnace as an inferred thrust fault. The curious occurrence of sheared quartz, muscovite, and limonite at some contacts and not others suggests a more complicated picture than purely conformable contacts.

V. STRUCTURAL GEOLOGY

1. General Statement

The major structural features in the Dover Plains area (Plate I) trend north-south. Deformation of the sedimentary series, according to the interpretation of Balk (1936, p.744 and 758), is largely caused by normal faults and eastward-dipping thrust faults that have disturbed the Precambrian basement complex. An additional longitudinal folding trending east-west is observed in the vicinity of Sherman Hill. It is expressed by the westward physiographic projection of gneiss and quartzite of East Mountain into the valley and the projection of the marble into the schist at this latitude. Further evidence of east-west folding is the eastward extension of the sedimentary formations through the gap of Wingdale between the Housatonic and Hudson Highlands gneiss blocks. Relations of metamorphic minerals with the structure and sheared east-west-trending pegmatites suggest that some deformation is later than metamorphism. Present structural, stratigraphic, and petrologic evidence indicates that all periods of metamorphism, folding, and faulting are not contemporaneous.

2. Major Structures

Major Period of Deformation - The major deformation of the carbonate rocks produced a series of steeply eastward-dipping isoclinal folds with a wavelength of 400 to 1000 feet in the eastern part of the valley. The stratigraphic succession is continuous across the valley with no repetition of the eastern

dolomites and quartzites in the western part of the valley; the succession is continuous through the Wingdale gap.

Balk (1936, p.702) called attention to the relation between strike and trend of isoclinally folded layers. An attempt was made to verify this in the vicinity of Ellis Pond. Here the major south-plunging folds dip off the Precambrian gneiss block and individual units of the Stockbridge from east to west although the local strike of compositional banding is approximately north-south. The structure of Units 2-C, 2-D, and 2-E on Cricket Hill suggests a similar interpretation. In smaller isoclinal folds the same relation between strike and trend occurs.

Sherman Hill Anticline - Throughout the valley the north-south-trending minor fold axes in the carbonate rocks vary in plunge from north to south. These variations are significant on the southeast extension of Nellie Hill and Sherman Hill. North of the latitude of Sherman Hill fold axes plunge 14 to 50 degrees north; south of Sherman Hill fold axes plunge 2 to 60 degrees south and are associated with the major south plunging folds in the vicinity of Ellis Pond. These fold axis variations and shallow north- and south- dipping compositional banding near locality 24 are interpreted as an east-west trending anticline. The axial region of the anticline continues eastward near locality 18 where the fold axis orientation has the same variations. A prominent set of nearly horizontal joints at locality 24 intersect the steeply

dipping compositional banding (Fig. 3) and may be associated with the anticlinal structure.

3. Minor Structural Features

General Statement - The major structures in the carbonate rocks cannot be interpreted without minor structures which are often the only clues to the structure in isoclinally folded and plastically deformed rocks. The following section is a description of foliation, compositional banding, boudinage mineral orientation, and the structures of small pegmatite bodies.

It is convenient when describing fold geometry to refer to a coordinate system (Cloos, 1946, p.5 and Hills, 1953, p.152). The axes a and b are in the foliation plane; c is normal to it. b is parallel to and a at a large angle to fold axes. Both a and b may be defined by linear elements in the rocks; b is a rotation axis and a is a direction of elongation or stretching. For definitions of stress, strain, plastic flow, and fracture see Jaeger, 1956, chapters 1 and 2.

Foliation and Compositional Banding - it is necessary to distinguish between primary bedding and foliation in the deformed carbonate rocks when interpreting the major structures. Rock foliation in the pure carbonate rocks is expressed by the parallel orientation of the long axes of recrystallized carbonate minerals. In many cases foliation occurs between layers differing in mineralogy and can be traced around the axes of folds.

In limestone or dolomite containing siliceous impurities (quartzite beds or schistose partings) the layers differing in mineralogy or texture are parallel to rock foliation and can be interpreted as primary bedding. There is no evidence as suggested by Barth (1936, pp.826-834) and Bain (1934, p.132) of compositional banding having been formed or altered by "magmatic solutions" which have permeated the sediments. Layers of quartzite or limesilicate in highly metamorphosed horizons can be correlated with similar or the same layers which are not as highly metamorphosed, and thus contain little or no limesilicate minerals. The more competent layers retain primary laminations, color differences, and possibly primary sedimentary features (Fig. 19). Where limesilicate layers occur in contact with recrystallized dolomite, the contact in thin section is sharp; there is no evidence for silica having diffused as a "pore liquid" selectively forming limesilicate bands or adding silica to the pure carbonate rocks. Whether or not these primary compositional differences can be used as unfailing criteria for structural interpretation depends on the intensity of deformation (cf. Figs 12 and 22).

Folding, plastic flow, and recrystallization have destroyed nearly all traces of primary bedding in the thick units of relatively pure dolomite. However, the intense deformation has not destroyed the compositional or color differences (Figs. 10 and 22). The foliation in these units may be the expression of fracture cleavage that cross-cuts

the compositional banding as indicated by Balk (1936, p.720). Foliation in the pure carbonate rocks is also parallel to the compositional banding and agrees with foliation in the more competent layers; only then is foliation a reliable criterion for the structure.

No concrete rules can be stated for the use of foliation, compositional banding, and primary bedding in the Dover Plains area in structural analysis. Structures in the more competent units are generally more detectable than those in the pure, massive carbonate units.

Boudinage - Boudinage occurs as the most striking minor structural feature in the area, occurring in all the carbonate rocks although rarely in the upper units of calcite marble. Its distribution is variable but increases consistently with intensity of deformation toward the south and east. Boudinage in the vicinity of Fox Hill (loc. 2) is restricted to some $\frac{1}{2}$ - $\frac{3}{4}$ -inch beds of light gray quartzite in small drag folds; dolomitic quartzite and chert are highly contorted but rarely exhibit separate boudins. The outcrops south of Bains Corner have more boudinage than at Nellie Hill. South of the short east-west bend in the Tenmile River to Pawling, N.Y. and east to Bulls Bridge, boudinage is developed in all the dolomitic units. Variations in boudinage are shown in Figures 12 to 23 in order of apparent increasing deformation. Each locality is described below:

Figure 12 shows interbedded dolomitic limestone,

arenaceous dolomite, and dolomitic sandstone with tensional fractures developed but separation of boudins does not occur unless resistant bed is thin, highly siliceous, and interbedded with pure dolomite on both sides. This locality is the axial region of a minor fold where boudinage should not be expected but relative to Figures 13 and 18, the units show less deformation in the axial region.

Figure 13 illustrates minor folds, in dolomitic sandstone showing separation of fractured units and plastic deformation of dolomite. This is neither boudinage in the sense of pure tensional origin nor do the fragments define a lineation parallel to the minor fold axis. A lineation defined by the edge of a tabular boudin, (Fig. 24-c) has a strike in the direction of the hammer handle and plunges nearly vertically. A lineation defined by the tiny crenulation axes in the lower right of the photograph strikes in the same direction and plunges north about 20 degrees. Here boudinage is not a \underline{b} - (fold axis) lineation.

Figure 14 illustrates boudinage of a quartz compositional unit which is concordant with drag folding. The boudinage lineation is parallel to the minor fold axis and plunges about 15 degrees north from the horizontal.

Figures 15 and 16 are of fractured units of gray quartzite in the limbs of isoclinal folds. Minor fold axes plunge from 5 to 20 degrees north and boudinage lineation plunges vertically with an orientation as shown in Figure 24-c. Boudinage here is not a \underline{b} lineation.



Figure 12.- Deformed layers of quartzite and schist in recrystallized dolomite. Locality 11 on Nellie Hill



Figure 13.- Fractured layers of quartzite and stretched schistose partings in recrystallized gray dolomite. Outcrop between localities 21 and 23 on Sherman Hill.



Figure 14.- Boudinage of quartzite layer and its relation to drag folds in the dolomite. Hammer rests on east-west joint surface beneath drag fold. Boudinage \perp lineation normal to joint surface. Locality 23 on Route 22 south of Dover Plains.



Figure 15.- Layers of fractured and boudinaged quartzite in dolomite. Compass points to fragment of quartzite separated quartzite bed on the right. Horizontal joint in the plane of the figure with a boudinage lineation normal to it. Another boudinage lineation parallel to \perp is in the plane of the figure and parallels the strike of compositional banding, Locality 17.

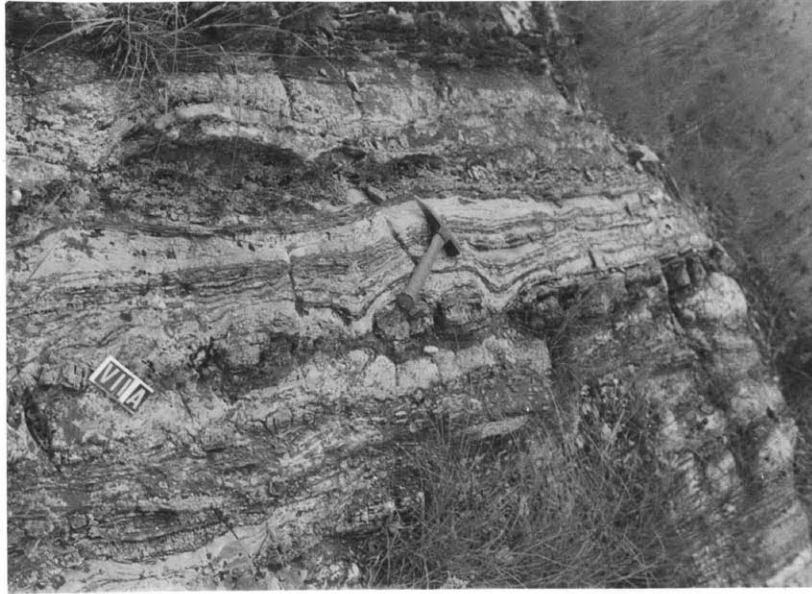


Figure 16.- Quartzite boudins in impure white dolomite. Flowage in the dolomite clearly indicated by the trace of schistose partings undulating between the boudins. Locality 19.



Figure 17.- Boudinage of quartzite in dolomite. Hammer handle rests beneath gray dolomite and separates the ends of the boudins. Locality 30 on Cricket Hill.



Figure 18.- Boudins of thinly banded quartzite in dolomite in the axial region of a minor fold. The curvature of the upper boudin is the trace of the axial surface of the fold. Locality 30.



Figure 19.- Pinch-and-swell structure in relatively incompetent sandy dolomite. Tip of hammer indicates possible primary scour-and-fill structure. Top of the steeply inclined beds to the bottom of the figure. Illustrates possible confusion between primary sedimentary features and minor structures. Outcrop on Route 22, 3 miles south of Wingdale.

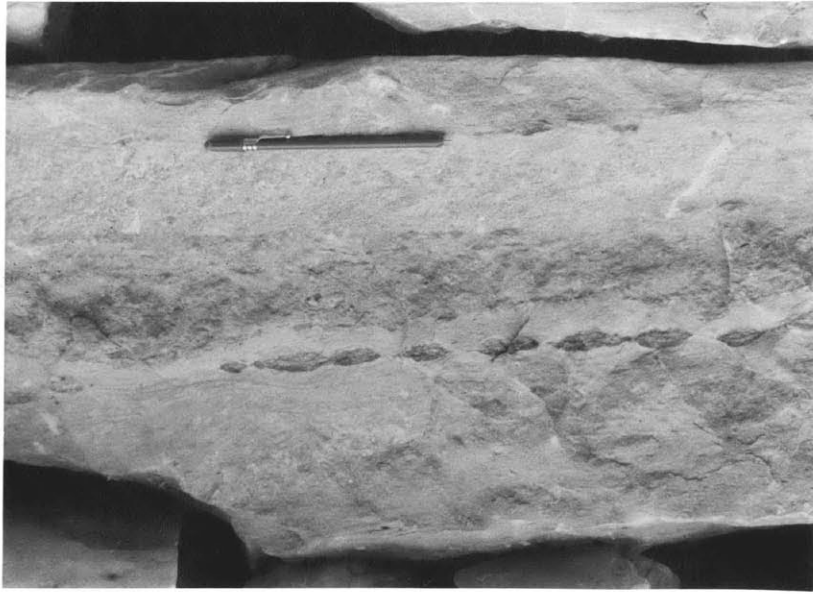


Figure 20.- Pinch-and-swell structure of calcite-phlogopite schist in dolomite. Same locality as Figure 19.

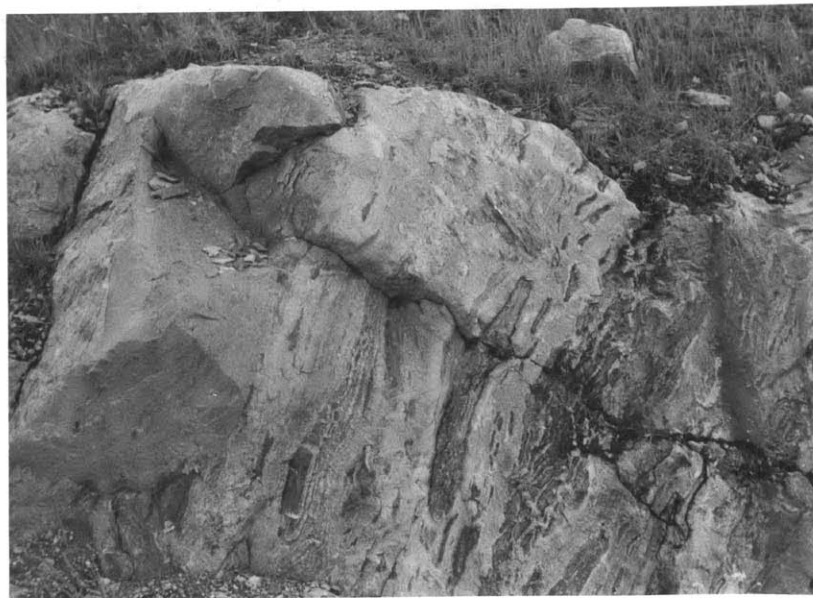


Figure 21.- Small fragments of sheared and boudinaged dolomitic quartzite in incompetent pure dolomite. East-west joint normal to compositional banding. Note how the dolomite has flowed between the fractured pieces of the competent layer. Pencil above large boudin is scale. Outcrop on Route 22, 4 miles south of Wingdale



Figure 22.- Deformed boudins of dolomitic sandstone. Note the rounded ends of the boudins and flowage structure in the dolomite. Hammer rests on contact between very coarse crystalline calcite marble and impure dolomite. Flow structure in the calcite marble gives the impression of relatively undeformed beds unconformably overlying the intensely deformed dolomite. Locality 42, Bulls Bridge.

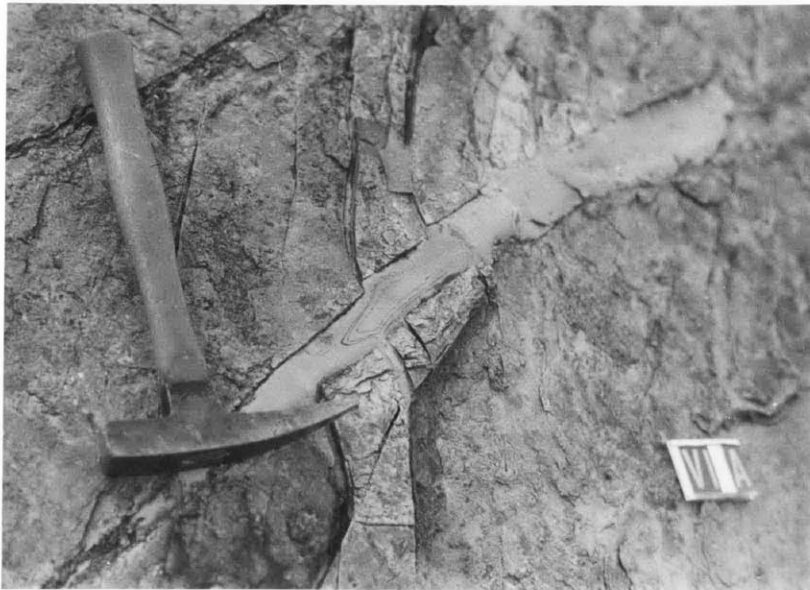


Figure 23.- Boudinage of quartzite layer (dark) in dolomite. Hammer rests on plane of compositional banding and lies across a large boudin which is separated by dolomite from the lower left to the upper right. Other small fractures parallel to the handle are filled with plastically deformed dolomite and the flow lines in the center of the figure indicate only one period of deformation with respect to the major and minor fractures and plastic flow. Locality 18 southeast of Dover Plains.

Figure 17 shows boudinage of a thick quartzite layer; the hammer rests beneath the pure gray dolomite which has flowed between the ends of the two boudins. The curvature of the dolomite above the end of the handle indicates the flowage. A set of transverse fractures are superimposed on the flowage in the dolomite. The boudins have well-formed sharp corners which are characteristic of the pure layers of quartzite.

Figure 18 indicates that boudinage is not restricted to the limbs of folds. The hammer rests beneath a remnant fold axis boudin which has been separated from the rest of the fold. The limbs of the fold are not shown but are beneath the figure; they are parallel to the sides of the figure. The traces of fractures normal to the compositional banding in the fold axis are visible. The fractures suggest a form of slip cleavage parallel to the axial plane of the fold. Tiny crenulations in the dolomitic quartzite and in the small schistose partings are in the plane of compositional banding and foliation of the rock.

Figures 19 and 20 are from a locality of relatively high deformation (south of the Dover Plains quadrangle) and illustrate "pinch-and-swell" structure in limesilicate, chert, and dolomitic layers. In this locality boudinage develops in various degrees depending on the apparent relative competency of the layer undergoing stress. Distinctly fractured boudins occur within inches of pinch-and-swell structures. Boudins vary in thickness from $\frac{1}{4}$ inch to 8 inches and from $\frac{1}{4}$ inch to 6 feet in length. In siliceous dolomite, boudins are

not clearly defined as in Figure 19. With increasing silica content in the recrystallized units there appears a greater tendency for more distinct development but the ends of the boudins are usually tapered. The nearly pure red quartzite layers develop sharp corners as Figures 15 and 17 especially if more than 4 inches thick. Thin layers of black chert form small pinch-and-swell boudins separated at distances of 2-3 feet as in Figure 20.

Figure 21 represents boudinage and tensional "shattering" of resistant layers. Note the small fragments fractured, folded, and separated by dolomite. A similar case is described by De Sitter (1956, p.102-103).

Figure 22 illustrates extremely coarse crystalline white calcite marble interlayered with moderately coarse calcite marble in contact with impure dolomite containing beds of recrystallized dolomitic sandstone and limesilicate minerals. Boudinage is altered by further deformation and the ends of the boudins are rounded. In the same area boudins of gray quartzite 6 inches thick develop with rounded edges and the boudins are isoclinally folded within the marble. Downstream the apparent deformation appears so intense that recognizable boudinage does not develop in the most resistant quartzite. The beds are stretched and sheared into thin fragments. The orientation of boudinage with respect to fold geometry is indeterminate.

The relation between boudinage and the major structure is often unclear. Cloos (1946, p.8) describes boudinage in its most general case:

"...a very common, but rather rarely observed structure, in rocks in which competent and incompetent layers alternate. The competent layers break, and the fragments separate. Incompetent material flows into the gap, or new minerals fill it. Boudinage can form by tension and elongation parallel to the fold axes or perpendicular to them and downdip the limbs of folds."

In the Dover Plains area boudinage occurs both parallel and normal to fold axes in the plane of foliation. Figures 24-a, -b, and -c illustrate the relation of boudinage lineation to the surface of compositional banding. The boudin is a tabular body whose longest axis defines b lineation in the usual sense (Fig. 14 and 24-a), and must be concordant with minor fold axes in the vicinity to be used as b lineation. When tensional stress along b produces fractures parallel to a, a blade-shaped boudin results as in Figures 23 and 24-b rather than a rod-shaped boudin. In some cases the result of b-axis tension is similar to Figure 24-c; this is rarely observed.

The examples of boudinage cited above indicate its variability in a single outcrop or locality. It is not always a fold-axis lineation but often develops normal to the fold axes as an a lineation. Thus boudinage cannot be used without knowing its orientation with respect to other minor structures.

The different types of boudinage forming in rock types of different composition suggest the possibility of establishing

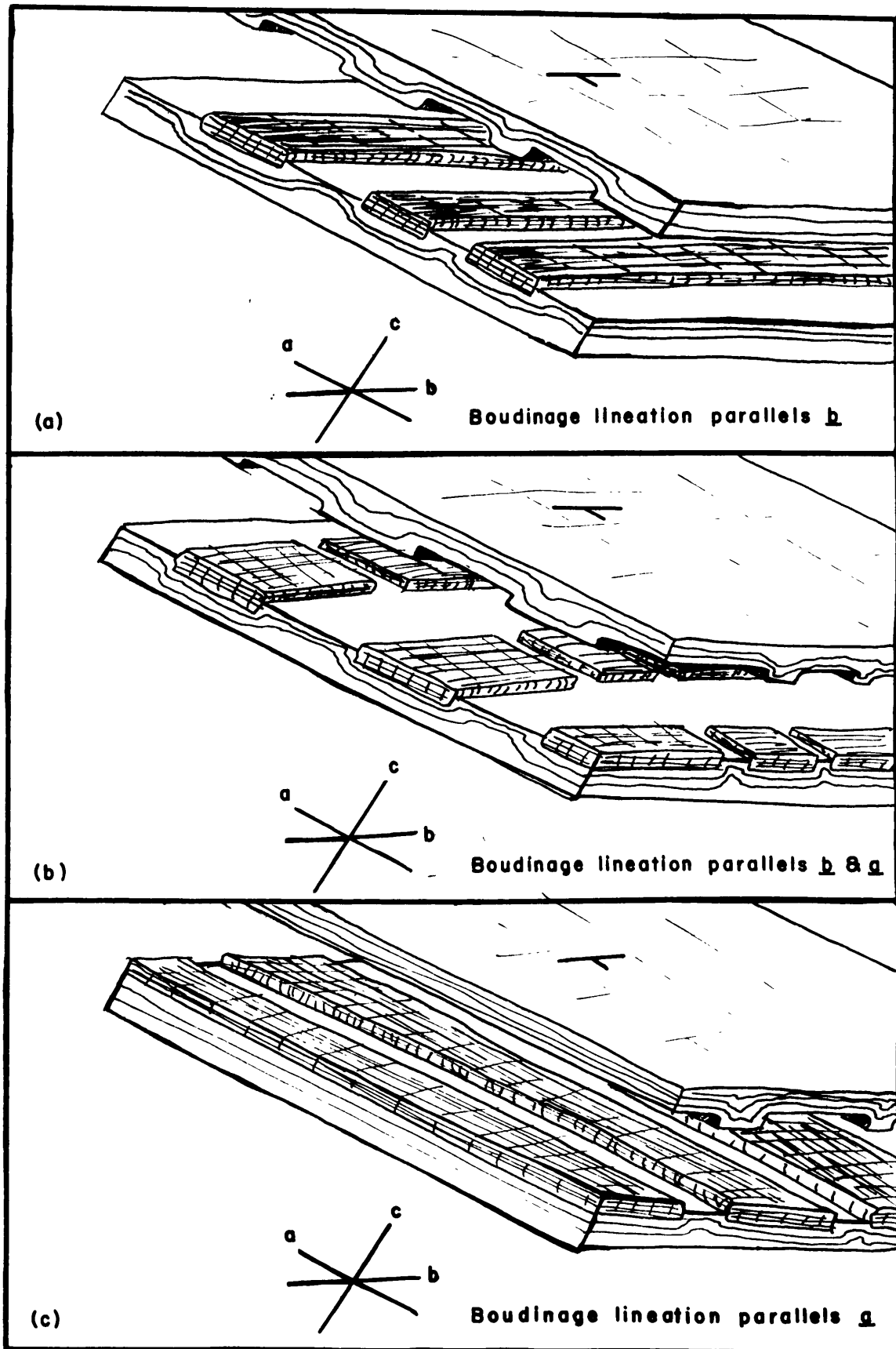


Figure 24.- The relation of boudinage-type structures to the coordinate system of a fold.



Figure 25.- Eastward-dipping isoclinal fold in competent bed of quartzite. b lineation defined by the axial line of the fold plunges 26 degrees south. Locality 10, 1½ miles southeast of Dover Plains.



Figure 26.- Sheared east-west trending pegmatitic quartz. Arrows indicate stretched and sheared fragments in the plane of dolomite foliation; the main part of the pegmatite is in the right center of the figure. Looking east at locality 45 southeast of Bain's Corner. Scale is 8 feet in the foreground.

a scale of relative competency. Thompson (1950) used boudinage to establish a scale of competency for rock units in the area of Ludlow, Vermont. Any competency scale derived in the carbonate rocks of the Harlem Valley should consider the individual layers in a rock unit rather than the unit as a whole. As stated above, boudinage varies in intensity from north to south such that some layers which develop boudins at Bulls Bridge may not develop boudins in the vicinity of Fox Hill or Nellie Hill. Any competency scale should therefore be derived within a small area. Boudinage formation also depends on the extent of recrystallization such that dolomitic sandstone in the vicinity of Nellie Hill will not fracture but flows instead. The same units near Cricket Hill or south of Wingdale are partially recrystallized into limesilicates which gives the layer a greater competency and tendency to form boudinage.

Minor Fold Axes - Pumpelly (1894, p.158) stated that "the degree and direction of the pitch of a fold are often indicated by those axes of the minor plications on its sides." This rule originally referred to minor folds of an anticlinoral or synclinoral structure but has been extended (Cloos, 1946, p.17; De Sitter, 1956, p.307-313) to include small drag folds formed by the relative deformation of competent and incompetent layers. In the Dover Plains area several types of minor structures can be interpreted as minor fold axes: 1) the larger axes of isoclinal folds; 2) tightly folded thick beds of quartzite

(Fig. 25); 3) drag folds in nearly pure dolomite (Fig. 14); 4) thin, competent layers of quartzite surrounded by incompetent dolomite (Fig. 12 and 13); 5) tiny crenulations of schistose partings in dolomite (Fig. 13).

Preliminary observations in the vicinity of Sherman Hill indicated that all types of fold axes (including the b lineation formed by the intersection of compositional banding and fracture cleavage) are not always in agreement, and that a variety of b lineation orientations occur in a single outcrop. A statistical approach is desirable but is beyond the scope of this work; the rock type of the fold axis should be specified with each measurement.

Structures of the Pegmatites* - The structural relations of the small tabular bodies of pegmatitic quartz which occur in several localities are important in relating the relative ages of deformation to metamorphism and the possibility that silication by a metasomatic "pore fluid" might have caused the limesilicate compositional layers in the dolomite.

At locality 45 an intensely sheared mass of pegmatitic quartz nearly 2 feet thick is concordant with the north-south foliation in the dolomite. The quartz does not resemble any of the quartzite beds in either the Cheshire quartzite or the

* Jahns (1955) defines pegmatites as "holocrystalline rocks that are at least in part very coarse grained, whose major constituents include minerals typically found in ordinary igneous rocks, and in which extreme textural variations, especially in grain size are characteristic" without reference to origin.

lower Stockbridge and has no characteristics of the metamorphosed sedimentary rocks.

A similar pegmatite body near locality 45, originally trending east-west and crosscutting the compositional banding in the dolomite, sheared, folded, and drawn out into small, thin bands which weather out as raised ridges parallel to the flow structure in the dolomite which trends north-south (Fig. 26). The pegmatite appears to have been emplaced and crystallized before its deformation.

At locality 27 a 6-inch thick sheared layer of pegmatitic quartz is emplaced concordantly with the compositional banding and foliation. A $\frac{1}{2}$ -inch layer of diopside surrounds the pegmatite where the quartz is in contact with the dolomite suggesting a reaction rim between quartz and dolomite. Shaub (1929) has described a similar rim of limesilicate minerals surrounding a pegmatite intruded into carbonate rocks associated with the paragneiss near the northwest margin of the Adirondack igneous massif.

The structure and mineralogy of the pegmatites indicate that they are discordant bodies in the carbonate rocks, presumably of igneous origin, and not related to the sedimentary rocks. Crosscutting pegmatites in the schist and limestone in the Dover Plains area were noted by Balk (1936, p.752) and in the Stockbridge limestone near Falls Village, Connecticut to the northeast by Agar (1935). Agar notes that quartz and microcline cut across the foliation planes and replace the minerals in an 8-inch bed of silicated marble

containing diopside, tremolite, actinolite, phlogopite, scapolite, and titanite.

Mineral Orientation - The diopside, tremolite, and actinolite crystalloblasts in the dolomite crystallized prior to the major period of deformation and have responded to flowage and folding in a manner similar to pebbles or siliceous layers in the dolomite. The diopside crystals in Figure 27 have been fractured, oriented with their longest dimension parallel to the direction of flow in the calcdolomite, and the corners of the well-formed crystals have been rounded or corroded by the deformation. At the same locality are many striking examples of rotated crystalloblasts with the longest dimension normal the direction of flow; the dolomite has flowed around the crystal forming calcite pressure shadows. Tremolite and actinolite have also been fractured and reoriented during deformation.

Calcite crystals are frequently aligned along the planes of foliation in the recrystallized limestone; the long axes of the crystals in the foliation plane define an a lineation.

Time Relation of Deformation and Metamorphism - The structural relations of the east-west trending pegmatites, boudinaged layers of recrystallized dolomitic sandstone, and the lime-silicate crystalloblasts indicate that the major period of deformation is later than the major period of metamorphism. Balk (1936, p.724) noted an example of fracture cleavage later than recrystallization and plastic flow in the dolomite near

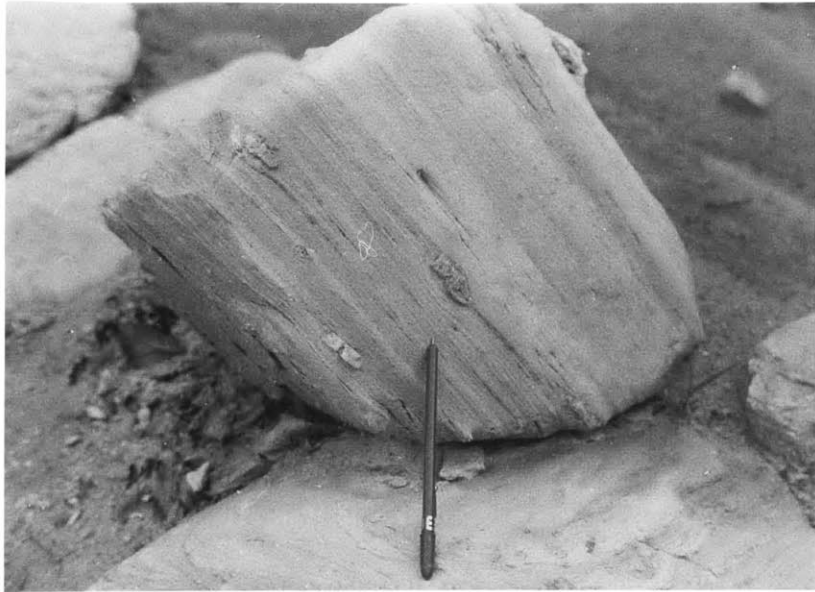


Figure 27.- Corroded crystalloblasts of diopside surrounded by flow structure of thinly banded calcdolomite. Locality 28, Cricket Hill.

locality 39 north of Webatuck. Crystallization of the lime-silicate minerals throughout the carbonate rocks appears to be pre-deformation with the exception of phlogopite which may be more closely associated with the deformation. The most recent recrystallization of the carbonate minerals is contemporaneous with the major folding of the sedimentary sequence as indicated by flowage of dolomite around boudins of recrystallized dolomitic sandstone; some fracture cleavage is later than carbonate recrystallization.

4. Summary

The carbonate rocks of the Dover Plains area have been subjected to at least two and possibly three distinct deformations: 1) the major deformation produced a series of steeply eastward-dipping, isoclinal folds in a continuous stratigraphic succession from the Cheshire quartzite on East Mountain; 2) a gentle east-west trending longitudinal folding; 3) the development of post-recrystallization fracture cleavage. The time relation between (1) and (2) is uncertain and the two may be contemporaneous; deformation (3) is definitely later than (1). The major period of metamorphism is earlier than any of the three deformations observed.

Minor structures generally conform with the local movement pattern in the larger isoclinal folds but various types of linear planar structures are a function of rock composition and are not always interchangeable as structural data. Boudinage should be checked against fold axes, and

fold axis data should be separated according to the rock type in which they occur.

VI. METAMORPHISM

1. Metamorphism of the Pelitic and Carbonate Rocks*

Barth (1936) studied the metamorphism of the Hudson River formation in Dutchess County and showed that metamorphism increases from northwest to southeast normal to the strike of foliation and exhibits three different mineral facies in order of increasing grade: 1) muscovite slate facies; 2) kyanite schist facies; and 3) sillimanite gneiss facies. The mechanism of metamorphism proposed by Barth (p.832) is:

"...the Paleozoic sediments were metamorphosed by the intrusion of various kinds of magmatic matter, contemporaneous with mountain folding... (and)...during the period of orogenesis, the sediments were heated and stewed in liquids of magmatic and anatectic origin, which reacted with the sediments and metamorphically transformed them into well-defined schists and gneisses."

Agar (1932) studied the metamorphism of the Salisbury schist overlying the Stockbridge formation in northwestern Connecticut and concluded that the intensity of metamorphism in the schist does not increase normal to the strike of foliation but normal to a line which makes a 30 degree angle to the east of the strike or, nearly north-south.

Metamorphism is used here according to the definition of Turner and Verhoogen (1951, p.368 and 375). Present observations indicate that two periods of metamorphism have altered the carbonate rocks:

* A detailed study of metamorphism in the Dover Plains area is beyond the scope of this work and only field observations are considered. The reader is referred to Barth (1936) and Carroll (1953) for additional detail and definitions.

- 1) The earlier period of metamorphism is of moderate to high thermal rank and increases in intensity from north to south. It is not associated with any major deformation or change in bulk composition of the rocks. Large, well-formed crystals of diopside and radiating clusters of tremolite crystals were formed and dolomitic sandstone recrystallized into stable limesilicate minerals. Calcite and dolomite may have recrystallized. Wingdale and Bulls Bridge are localities of moderate thermal rank (diopside-calcite-quartz-andesine); the dolomites near Bain's Corner contain tremolite indicating a lower grade; and quartz-calcite-dolomite is a stable assemblage near Nellie Hill. The pegmatites probably were emplaced in this period.
- 2) The later period of metamorphism is associated with the major period of deformation. The earlier formed limesilicates were subjected to deformation and calcite and dolomite flowed as a plastic material around the more competent fractured siliceous layers and recrystallized. No limesilicate minerals appear to have crystallized during this period.

2. Formation of Diopside Crystalloblasts.

With the aid of stratigraphic control it is possible to trace individual horizons in the carbonate rocks from localities of high grade metamorphism north to localities of lower

grade. Diopside is profusely developed in the dolomite and calcdolomite of unit 2-G (Fig. 27) near the contact between the upper and lower sequences and is confined to compositional layers. In the same locality (28) quartz pods and pegmatitic quartz have thin rims of diopside where in contact with dolomite. Small grains of quartz in the same dolomite layers have not been found.

Near locality 13 of Nellie Hill small rounded grains of quartz occur in the calcdolomite near the contact between the upper and lower sequences.

The sedimentary origin of the silica is verified in part by the occurrence of both quartz and limesilicate confined to compositional layers rather than random dissemination throughout the rocks. Barth's (1936, p.831) mechanism of magmatic water and silica being introduced into the carbonate rocks is unnecessary. There is no evidence for a change in the bulk composition of the rock in the Dover Plains area. It appears that the quartz grains have reacted with the dolomite to form the large diopside crystalloblasts. Any mobile silica during the period of metamorphism has been emplaced in the form of pegmatites.

3. Summary

The present work indicates that two periods of metamorphism have altered the carbonate rocks. The mechanism of metasomatism is not necessary to produce limesilicate minerals in the dolomite or dolomitic sandstone.

VII. CONCLUDING STATEMENT

Results of the present work in the Dover Plains area appear to verify the conclusions of Balk (1936) and Carroll (1953) that the highly deformed and metamorphosed carbonate rocks are of Cambro-Ordovician age.

The sequence of dolomites and limestones is a continuation of the Stockbridge formation of western Massachusetts and the subdivisions bear a striking resemblance to the descriptions of Knopf (1946), Herz (1958), and Cady (1945) in areas to the north where fossils have been found in the carbonate rocks. In particular, the units of the upper "calcitic" Stockbridge appear to be very similar to the limestone sequence of Chazy-Trenton age described by Cady in west-central Vermont.

The Carbonate rocks in the Dover Plains area form a continuous sequence from east to west across the Harlem Valley as indicated by structural relations, the gradational nature of the schist-marble contacts, and a comparison with the stratigraphy of the Cambro-Ordovician carbonate rocks to the north. The same subdivisions are continuous across the southern end of the Housatonic gneiss block into the Housatonic Valley of Connecticut.

The relations observed between metamorphism and deformation indicate at least two periods of metamorphism and three periods of deformation some of which may be contemporaneous. It appears that the major period of metamorphism was largely

completed before the major period of deformation. The major deformation caused recrystallization and plastic flow in the carbonate minerals whereas diopside, tremolite, and actinolite were developed before deformation. The trend of increasing metamorphic grade from north to south in the carbonate rocks is not in agreement with a northwest-southeast increase parallel to the strike of foliation in the pelitic rocks proposed by Barth and Balk (1936).

The intriguing problems of structure, stratigraphy, and metamorphism of the carbonate rocks in the Dover Plains quadrangle have only been briefly surveyed in the present study and any conclusions are certainly tentative.

VIII. SUGGESTED WORK

The scope of this report is limited and the geology of the Dover Plains area requires many more detailed observations before definite conclusions on stratigraphy, structure, and metamorphism can be made. The following problems remain to be investigated:

Stratigraphy

- 1) Each of the proposed stratigraphic units are poorly defined and cannot be used as map units in some localities. A more workable subdivision is necessary.

The sequence in the Dover Plains area appears to be quite similar to the succession of the carbonate rocks in west-central Vermont (Cady, 1945). A familiarity with the Vermont area would be useful in studying this area.

- 2) Between Dover Plains and Wingdale the texture and mineralogy of **Unit 2-4** and **Sequence 3** undergo marked changes from low to moderate metamorphic grade. These units should be traced south to Patterson, N.Y. where the sedimentary rocks are interrupted by the Highlands gneiss block, and then traced into Westchester County where the age of the Inwood marble is a matter of controversy.

The absence of the Lowerre quartzite in the Poundridge area (Scotford, 1956) and near Peekskill (Bucher, 1951) suggest that the carbonate rocks were

deposited directly on the Pre-cambrian gneiss. The overall stratigraphy of the Stockbridge may be useful in determining stratigraphic position of the Inwood.

- 3) The more competent quartzitic units should be further examined for fossils and primary sedimentary features.

Structure

- 1) The detailed structural analysis near Bain's Corner should be carried further in the valley.
- 2) Complementary structures to the Sherman Hill anticline can be determined with detailed fold axis data.
- 3) The relation between strike and trend should be verified in the vicinity of Cricket Hill and the structure of the Ellis Pond major folds can be broken down into smaller structures showing strike and trend relations.
- 4) The Dover Plains area is an excellent source for studying the interrelations of minor structures and their relation to major structures. The variability of one minor structure with rock composition should be considered. Boudinage and fold axes illustrate this.
- 5) The time relation between the "Sherman Hill folding" and isoclinal folding has not been determined. There is evidence for the Sherman Hill fold being both pre- and post-isoclinal folding.

Metamorphism

- 1) The suggestions made ^{about} the relations of the several periods of deformation and metamorphism require further verification.
- 2) North-south variations in metamorphic grade have been observed elsewhere (Dana, 1885 and Agar, 1932) in the vicinity of the Dover Plains area. The major period of metamorphism may be associated more closely with the igneous rocks to the south which may have produced a contact aureole in the sedimentary rocks.
- 3) The mechanisms of metasomatism proposed for the origin of silicate minerals in the carbonate rocks appear to be products of a vaporous imagination rather than fact. The petrology and bulk composition of specific stratigraphic horizon should be studied with respect to increasing metamorphic grade. (The chemical analyses given by Barth (1936) are not based on stratigraphic control.) Whether or not quartz is a primary sedimentary constituent of Unit 2-G remains to be verified in areas of lower metamorphic grade.
- 4) Stratigraphic control in the metamorphosed carbonate rocks may eliminate one of the variables in interpreting the change in C^{13}/C^{12} and O^{18}/O^{16} ratios with increasing metamorphic grade.

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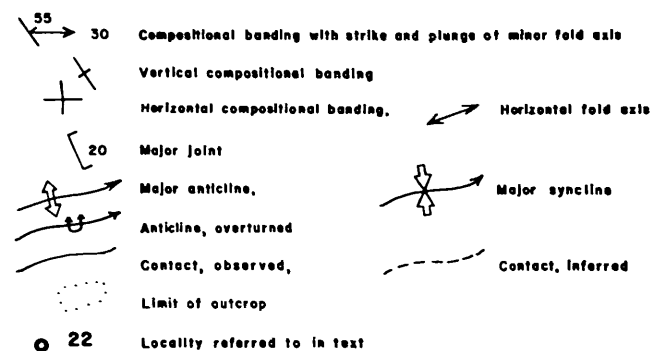
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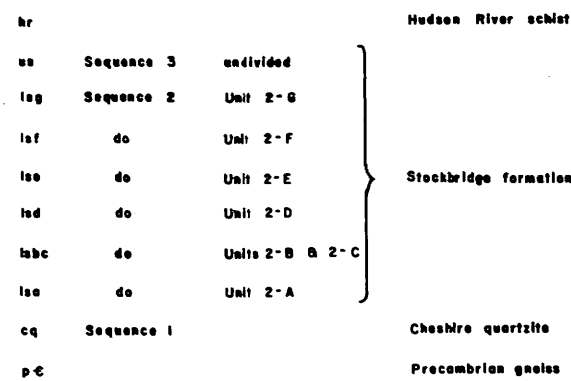
GEOLOGY AND STRUCTURE OF THE DOVER PLAINS AREA, NEW YORK

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STRUCTURE SYMBOLS



FORMATION SYMBOLS



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DAVID R. WALDRAM, 1960

