phibole which retain their premetamorphic igneous or metasomatic pattern.

The amphibolites of the Poundridge area reveal no positive proof of origin. However, there is evidence that metasomatism of carbonate layers and metamorphism of basic rock has contributed to their formation. Rarely can particular occurrence be assigned to an exact origin. Some of the amphibolite layers in the Manhattan schist which can be traced through the zone of the Bedford augen gneiss and into the epidiorite mass southeast of Bedford (Table 12, specimen 80) are of igneous origin. The other amphibolites in the Manhattan schist and those in the Fordham gneiss have no observable connection with an igneous body. Though the evidence is weak, their mineralogy places them in the category of amphibolites derived from a carbonate rock. Unlike most igneous amphibolites, they have a larger proportion of hornblende than plagioclase and contain appreciable amounts of quartz and biotite (Williams *et al.*, 1954, p. 243).

Additional petrographic evidence favors a sedimentary origin for some amphibolite layers in the Fordham gneiss. Two transition specimens, an amphibolite and a marble, have been studied. Specimen 49 (Table 10) from the Poundridge mass is a typical amphibolite except that it contains a small percentage of possibly remnant carbonate. Specimen 96 (Table 11), from a marbel layer in the Fordham gneiss east of Lake Kitchawan, contains an appreciable proportion of diopside, scapolite, tremolite, and plagioclase in addition to the dolomite. As noted by Adams and Barlow (1910, p. 104) this could represent an early stage in the transition from marble to amphibolite. It may be significant that no marble layers were found in the Fordham near the Poundridge granite while they are common elsewhere, presumably out of range of the granite's influence.

Structural Elements

Introduction

The structural elements described together with the stratigraphy and map pattern, are the basis for the structural interpretation. In the interest of keeping fact and interpretation separate, the proposed structural solution is contained in the section following those which describe the structural elements.

The geographic orientations of structural elements are read from a 360-degree scale with north at 0°. An east-west strike is thus a strike of 90°, the smaller angle being used in each case. Some features are presented in statistical diagrams (Figs. 4, 5, 6). These diagrams are the lower halves of equal-areal net projections oriented into geographic position.

Regional Setting

The foliation and formational boundaries of the New York City group strike northeastward throughout New York City and southern Westchester County. However, in northern Westchester and Putnam counties these two elements swing in large arcs of several miles radius until they are truncated by the north-east-striking Siscowit granite fault. This distortion is interpreted as the result of large-scale secondary folding in response to movement to the south or southeast.

Bedding

No feature which can definitely be ascribed to bedding was found in any rock. The position of the broad gneissic bands in the Fordham gneiss, which are probably products of metamorphic differentiation, may be controlled by original bedding. The conformable contact between the Inwood marble and the Manhattan formation gives a fairly accurate indication of the general bedding orientation within these formations. Fluhr (in a report of Board of Water Supply of City of New York, 1941, available at Engineering Societies Library) reports the presence of a bedding foliation in the Manhattan formation which is largely obscured by later schistosity, and a micaceous layering in the Inwood marble which might possibly be bedding.

This lack of definite bedding planes in an area of intense deformation and metamorphism handicaps but does not prevent the delineation of the structural picture and increases the importance of the remaining structural elements.

Foliation

Foliation is prominent in all rocks in the Poundridge area. The Manhattan formation and Inwood marble exhibit a schistosity which is considered a coarsened flow cleavage as defined by Leith (1905; 1923). In a few places this schistosity in the Manhattan formation is crinkled by incipient fracture cleavage (Leith,

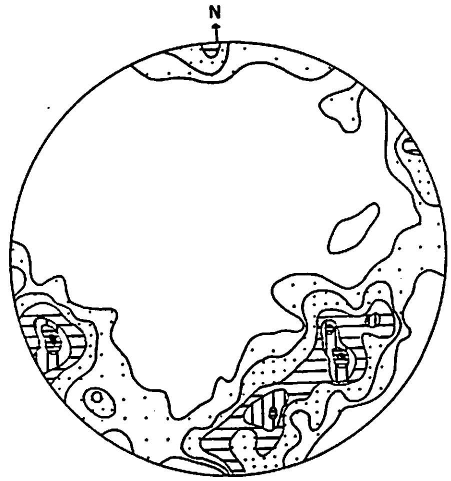

Figure 4.—Stereographic Projection of Poles of Foliation
Maxima 6 per cent

1905; 1923). The cleavage planes are so distorted that a determination of their orientation is difficult. The banding of the Fordham gneiss, too coarse to be called schistosity, is referred to as the gneiss foliation. The planar flow structure of the Poundridge granite is termed flow foliation. All these foliations, except the fracture cleavage, are conformable. With minor deflections, the strikes of the foliation of all the rocks in the mapped area form a series of concentric arcs centered just to the west of the Poundridge mass (Pl. 4). Thus the strike ranges through all angles from 0° to 180°. The dip, where not vertical, is northward. This pattern is illustrated statistically in Figure 4 where 300 poles of representative foliation planes have been plotted stereographically. The breached girdle pattern indicates a variation in strike through 360°; if the girdle were rotated into the periphery of the projection, it would be continuous. The scarcity of poles in the northern portion of the projection shows the lack of dip to the south. The two maxima in the southeastern and southwestern quadrants are significant only in that they indicate the trend of the most commonly exposed rock.

These foliation trends are completely foreign to normal Appalachian structures which are characterized by strikes to the northeast.

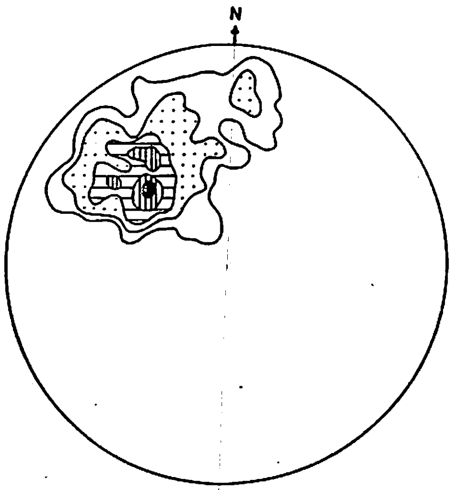

FIG. 5.—STEREOGRAPHIC PROJECTION OF LINEATION
Maximum 24 per cent

Lineation

Sander's (1930, p. 119) co-ordinate system is used: *b* is the fold axis; *a* is perpendicular to *b* in the movement plane; and *c* is perpendicular to *ab*. Fold axes will be discussed later.

The attitude of all lineations is shown statistically in Figure 5, which shows the strong preferred orientation plunging 45–50° NW. This lineation is believed to lie in *b*, the axis of latest folding, even though its position in relation to the noses of the folds in map view seems to indicate an *a* orientation. Perhaps this lineation was controlled by a thrusting movement from the northwest.

The most common lineation is alignment of elongated minerals (Pl. 3, fig. 2). In the Fordham gneiss small biotite and hornblende crystals are oriented and concentrated to produce delicate lines on the foliation planes. In the Manhattan formation this lineation is finer, the individual mineral being invisible. A strong orientation of hornblende prisms expresses the lineation in some amphibolite outcrops. In many places a light-colored mineral lineation in the Poundridge granite and Fordham gneiss consists of small quartz pencils, and commonly pods of hornblende or garnet constitute the lineation in the Fordham gneiss. A small-amplitude crinkling on the foliation surface is the most common lineation in the Manhattan formation.

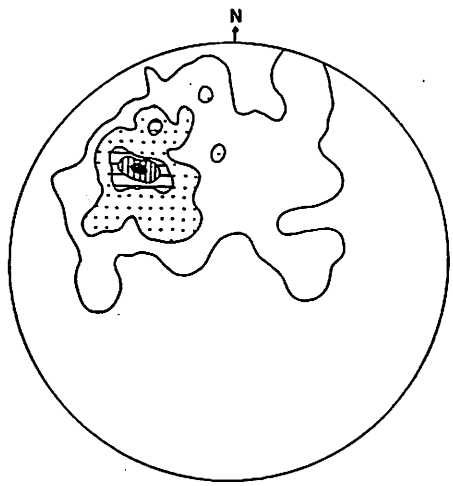

FIGURE 6.—STEREOGRAPHIC PROJECTION OF FOLD AXES
Maximum 16 per cent

Boudinage structure is found in the Fordham gneiss in several places. The boudins, usually less than a foot thick consist of amphibolite or feldspathic layers. The troughs which lie in the necks between the boudins constitute a lineation paralleling the other lineations. Boudinage is abundant near the outer contact of the Poundridge granite with the Fordham gneiss. This fact is important, since boudinage is usually a product of stretching perpendicular to the lineation. Thus, it indicates extension along the outer fringe of the Poundridge mass and tends to support the idea of axial-plane folding.

Prominent slickensides of the mullion-structure type are present on the exposed fault plane of the Siscowit granite fault.

Fold Axes

The orientation of fold axes is remarkably consistent for an area in which foliation is so variable. The statistical diagram (Fig. 6) shows a strongly preferred orientation, plunging about 45° NW., almost identical to that of the lineation. The fold axes are also considered to lie in

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Drag Folds

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b, the axis of latest folding. There is again, however, the possibility that this lineation parallels the movement direction of the major thrusting from the northwest.

The orientation of these fold axes was measured directly from generally small-amplitude folds (a fraction of a foot to a few feet) on the foliation surface. A few larger folds with amplitudes up to 300 feet were noted in the Fordham gneiss.

Drag Folds

Small drag folds are common in the Fordham gneiss, and there are a few in the Manhattan formation. The study of these folds aided in elucidating the broad structural features and is a base for some of the interpretation.

The direction of shear shown by the drag folds on the northeastern portion of the Poundridge mass indicates an upward movement affecting the exterior foliation bands in relation to the interior bands. Thus, there is a strong suggestion of an anticlinal structure in the Fordham gneiss. The axis of this fold trends along the outcrop area of the Poundridge granite. If the intrusion of the granite had caused the drag folding, the shear senses would be opposite that observed. It appears likely that the granite was intruded into the core of a pre-existing anticlinal fold.

At the summit of Titicus Mountain in the northern belt of Fordham gneiss some drag folds have vertical axes. The shear indicates that the northwestern portion of this belt moved to the northeast as would result from differential slippage of foliation planes during the bending of the gneiss mass into the arcuate shape (Pl. 4).

Drag folding in the Manhattan formation half a mile south of the village of Pound Ridge indicates the position of a major synclinal axis lying along the center of the schist and Bedford augen gneiss belt, and plunging southwest. This agrees with the stratigraphic evidence that the Manhattan formation is the youngest in a synclinal fold, being flanked on both sides by older Inwood marble and Fordham gneiss.

Drag of the foliation at the contacts of many pegmatite veins indicates that intrusion was upward.

Faults

The area which was mapped in detail (Pl. 4) lies between two major faults, the Highland gneiss fault on the northwest and the Siscowit granite fault on the southeast. Deformation of the intervening area is interpreted as a result of large-scale squeezing of pre-existing structures as the Highland gneiss block moved upward and southeast toward the Siscowit granite. The granite acted in part as a buttress, but also moved in the direction of the last tectonic transport.

The reverse fault separating the Precambrian Highland gneiss from the Inwood marble (Pl. 1), although not within the area mapped in detail, has been well described (Balk, 1936, p. 737; it is of primary importance to the structural interpretation. The fault has been traced from near Danbury, Connecticut, westward to Brewster, New York, thence southwestward through Croton Falls and Lincolndale. Shears indicate a thrusting of the Highland gneiss to the southeast over the Inwood marble. The steep dip of the fault plane indicates a large vertical component.

Structural evidences of faulting are not always present along the fault trace. Strong lineations and closely spaced foliation are locally abundant near the fault, but in many places are absent. The best evidence of faulting is stratigraphic since the Precambrian Highland gneiss constitutes the hanging wall above the younger Inwood marble along the major portion of the fault.

A major fault separating the Siscowit granite on the east from the Fordham gneiss-Inwood marble-Manhattan formation group to the west was traced from a point near Ridgefield, Connecticut, southeastward as far as Highridge, Connecticut.

As shown clearly on Plate 1 the fault causes the truncation of successive belts of Inwood marble, Fordham gneiss, Inwood marble, and Manhattan formation against the Siscowit granite mass. The contacts between these formations meet the fault trace at angles of about 20°.

Structural evidence of the fault, although not abundant, is striking. Slickensiding and stretching have produced prominent mullion structure in the Siscowit granite near the fault trace just east of Trinity Lake. The rods, up to 4 inches in diameter, plunge down the foliation plane at the maximum angle. Also the granite foliation is so closely spaced that the rock is schistose. Both features are lost and the rock becomes typically massive 100 feet away perpendicular to the strike.

This coarse lineation was also observed in a Fordham gneiss exposure near the fault. A light slickensiding on the foliation planes indicates faulting in the adjacent schist and marble.

A northwest-southeast direction of fault movement is strongly implied by the lineations near the fault, but the sense of fault displacement cannot be positively established because the relative ages of the fault blocks are not known. Since the fault planes dip northwest and the movement of the Highland gneiss block was to the southeast over the middle block, it seems somewhat more likely that the middle block also moved up to the southeast over the Siscowit granite, thus making the fault a thrust. Further work is necessary to definitely establish the movement relationships.

The probable existence of a fault separating the northern from the southern portion of the Poundridge mass is indicated by the offset Poundridge granite-Fordham gneiss contact across the east-trending valley of the Cross River (Pl. 1). The width of outcrop of the Poundridge granite is much less to the north than to the south of this line, indicating that the northern block is probably downthrown. However, there is no structural evidence of the fault; it is not known whether the fault is normal or reverse.

Fluhr (in a report of Board of Water Supply of City of New York, 1941, available at Engineering Societies Library) reported extensive evidence of shearing along the Fordham gneiss-Inwood marble and Inwood marble-Manhattan formation contacts exposed in the Croton aqueduct tunnel. Major displacement is not indicated, and evidence of this faulting is not commonly seen on the surface.

Interpretation

The area in northern Westchester and Putnam counties has undergone two distinct stages of deformation. Whether these stages are part of a single orogenic period or are widely separated in time is not known. They are characterized by deformational movements in two different directions.

From New York City to just southeast of the Poundridge area, the New York City group is isoclinally folded with the axial planes striking north-northeast and dipping to the northwest. From this point northeastward to the Highland gneiss block, the axial planes are themselves folded, causing the formational belts and foliation planes to swing in great arcs around the Poundridge mass until they abut the Siscowit granite fault (Pl. 1). To the northwest the axial planes are more tightly folded where they have been squeezed against the Highland gneiss block.

The northeasterly trend of the original isoclinal folding parallels the Appalachian fold axes and probably resulted from northwesterly tectonic movements. Later folding of the axial planes in the northern area could have resulted only from movement south or southeastward (Pl. 1). It is doubtful that the original folding is the same age as Appalachian folding, since pegmatites in the Bedford area, which were emplaced during or just following the last folding, have been dated as late Ordovician (Muench, 1931). If a large time interval separated these two deformational movements, possibly the earlier one is Precambrian, and thus the New York City group is also Precambrian. Since no data on the time interval are available, no conclusion as to the age of the New York City group is warranted, other than that it is no younger than late Ordovician.

The foliation in the Poundridge granite, although harmonious with that of the enclosing Fordham gneiss, is considered a primary flow structure. The amphibolite and less common gneiss inclusions are invariably aligned with their long dimensions paralleling the foliation strike even though in a few places they have been rotated so that their internal foliation meets that of the granite at a large angle. Large books of biotite parallel the strike of foliation at many places within the granite.

A large xenolith of partially assimilated gneiss approximately 100 by 500 feet occurs in the granite along the Fire Tower road on the eastern side of the Poundridge mass. The gneiss foliation trends east-west and makes an angle of about 70° with that of the granite and the

Fordham gneiss, attesting to considerable rotation. A discrepancy in the foliation strike in the northeastern part of the Poundridge granite (Fig. 7) probably indicates another rotated result of an east-west movement, bending the original axial planes into broad folds.

Axial-plane folding may not be described in the same terms as normal folding since it does

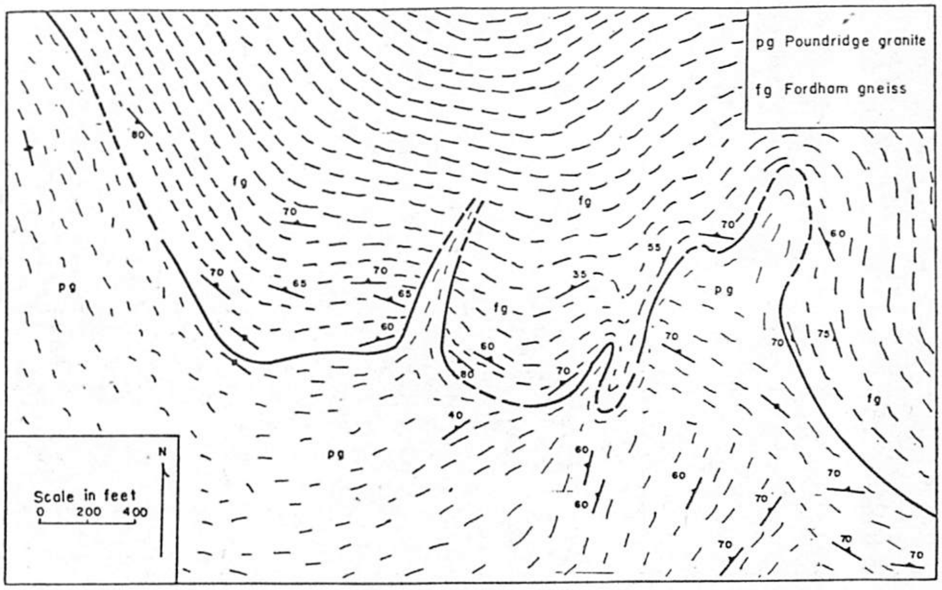

Figure 7.—Table Plane Map of Poundridge Granite-Fordham Gneiss Contact at the Northeastern Margin of Poundridge Mass

Though mostly concordant, the contact in places is transgressive. The discrepancy in the foliation strike in the Poundridge granite is seen in the southeastern portion of the map.

gneiss block whose borders with the granite have become blurred.

The information obtained from drag folds in the adjacent gneiss and the overall structural interpretation lead to the conclusion that the Poundridge granite probably was intruded parallel to the folded axial plane of an anticline of Fordham gneiss. It is probable that the granite moved upward for a short distance only from its enclosing envelope of migmatite with which it is still closely associated. Whether the intruded material was magmatic or rheomorphic remains unknown. That the granite was not intruded before the final deformation of the Fordham gneiss seems definite since evidence of post-consolidation disturbance of the granite is lacking.

Figure 8 shows diagramatically the application of the concept of axial-plane folding to three formations which were originally folded so that their axial planes were vertical, striking east-west. The area has been refolded as the not result in anticlines and synclines in the usual sense. Also, as the movements causing axial-plane folding would generally act in a roughly horizontal direction, the axes of the axial-plane folds would tend to be vertical and the terms trough and crest would lose their meaning. However, new terms need not be applied for the concept of axial-plane folding is relatively simple and may be adequately described by use of maps and sections.

Of primary importance in the interpretation of the structure resulting from axial-plane folding (Fig. 9) is the concept of the conformable stratigraphic relationship of the Fordham gneiss-Inwood marble-Manhattan formation group. If that concept is accepted, the map pattern of these formations, and additional structural evidence, allows no other interpretation. Reasons for believing that the New York City group is a conformable one need not be repeated, but it is pertinent to point out that no structural evidence of a major fault separatsuperposed folding

ing the Fordham and Inwood, as postulated by Balk (1936) and others, was found. Except where all three formations are faulted against the Siscowit granite, the Fordham is never

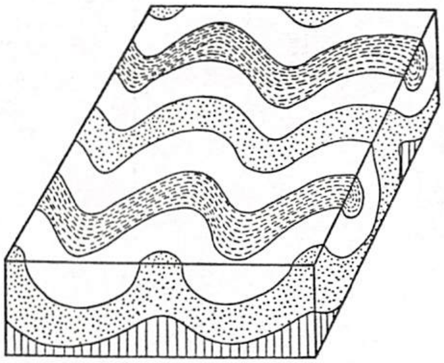

FIGURE 8.—DIAGRAMATIC REPRESENTATION OF AXIAL-PLANE FOLDING PRINCIPLE

Beds were first isoclinally folded with axes trending east-west. They were then refolded, due to east-west compression, resulting in axial-plane folds.

mile east of Lake Kitchawan (Pl. 3, fig. 1). There the Fordham gneiss belt is quite narrow. In addition, the shear sense of drag folds in the Fordham gneiss in the Poundridge mass suggests that an anticlinal axis follows the crescent-shaped exposure of the Poundridge granite within the gneiss.

(2) Stretching on the outer edge of the Fordham gneiss belts as a result of bending during axial-plane folding is indicated by boudinage. This structure is found along the outer edge of the Poundridge mass particularly in the south-facing escarpment. There the lineation produced by the necks between the boudins plunges northwest. Thus, the extension which produced the structure acted in a direction paralleling the outer contact of the gneiss.

(3) The orientation of the fold axes of the axial-plane folding may be read from the numerous measurements of fold axes and lineations made throughout the area (Figs. 5, 6). The northwest plunge of these elements indi-

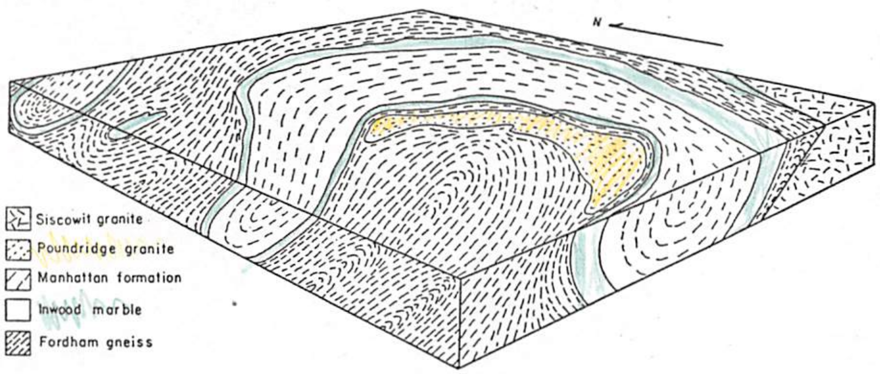

FIGURE 9.—BLOCK DIAGRAM OF A PORTION OF THE POUNDRIDGE AREA SHOWING AXIAL-PLANE FOLD INTERPRETATION

found in contact with any formation except the Inwood.

The existence of axial-plane folding is brought out on Plate 1 which shows the foliation and formation belts curving in large arcs around the Poundridge mass. The arcuate pattern of the anticlinal and synclinal axes is also indicated.

Additional evidence of axial-plane folding may be summarized as follows:

(1) That the belts of Fordham gneiss are anticlinal and not thrust blocks is supported by a preserved isoclinal fold a quarter of a

cates that the axial-plane folds are tilted to the southeast.

The second deformational stage, which produced axial-plane folding in the pre-existing northeast-trending isoclinal folds, appears to be the result of large-scale thrusting from the north and northwest. This movement was caused by the shifting of the Highland gneiss block south and southeastward toward the Siscowit granite mass, which may have acted as a buttress. Thus the intervening area was profoundly squeezed.

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