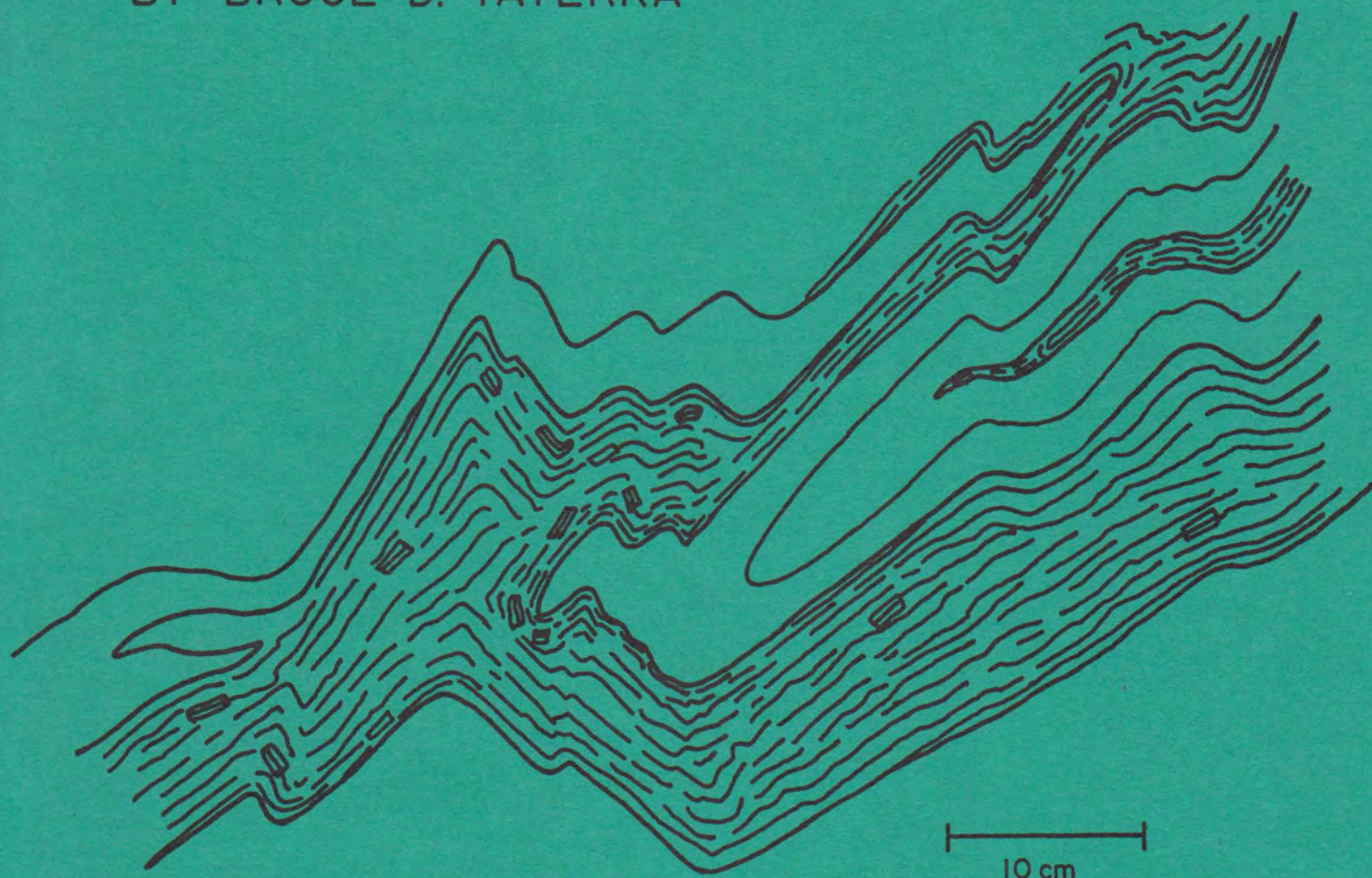


BEDROCK GEOLOGY OF CENTRAL PARK, NEW YORK CITY

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BEDROCK GEOLOGY OF CENTRAL PARK, NEW YORK CITY

(M.S. Thesis)

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1. Geologic Map of Central Park (in two parts)
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ABSTRACT

The rocks of Central Park consist of the Eocambrian-Cambrian Manhattan Formation and the Lower Ordovician Schist and Granulite Member of the Hartland Formation. These units lie on opposite sides of Cameron's Line, a major Taconian thrust fault, which appears to pass through the Park in an area of poor exposure. Three informal members have been identified and mapped in the Manhattan Formation. The lowermost 110th St. Member is a smooth, brown-weathering, garnet-mica schist. The overlying Blockhouse Member is a distinctive gray, 'knotty'-weathering, garnet-mica-kyanite-magnetite schist. The East Meadow Member is a brownish-gray, smooth-weathering, garnet-mica-kyanite schist that appears to be a layer within the Blockhouse Member. The Schist and Granulite Member of the Hartland Formation consists of gray-weathering muscovite schist with abundant interbedded fine-grained quartzose granulite. Fine-grained, black amphibolite beds are common in both the Hartland Formation and the two upper units of the Manhattan Formation.

The features seen in map and outcrop pattern are explained as the product of early thrust faulting followed by three major phases of folding. Early thrust faults were not observed, but can be demonstrated by stratigraphic relationships. First-phase folds are isoclinal and recumbent with east-west-trending hinge lines. These folds are rarely seen, but their axial planar foliation subparallel to bedding is well developed. Second-phase isoclinal recumbent folds plunge gently southwest and deform bedding and first-phase foliation. Third-phase upright folds also plunge southwest and deform earlier structural features throughout the Park. First- and second-phase folds are believed to be the result of the Taconian orogeny, while the age of third-phase folds is either Taconian or Acadian. Hook-shaped interference patterns in outcrop and map pattern are the result of second- and third-phase fold interference. Boomerang (heart) patterns are observed in outcrop only and are interpreted to be the result of the interference of first- and third-phase folds.

Thin section study of aluminous schist samples suggests that there was an early garnet-sillimanite grade metamorphism which is Taconian in age and is associated with the dominant metamorphic foliation. This was followed by a late phase of metamorphism under conditions of the kyanite-staurolite-garnet zone. The age of the late metamorphism is not well established in relation to structural features, but it is believed to be Taconian.

INTRODUCTION

"The area had since become a pesthole, grown to briars and poison ivy, although it had a census of some 5,000 squatters domiciled in hovels and shanties. Mongrel dogs roved in packs and the air hung putrid with the aroma of stables, pigsties, and bone factories. Converting the spot into a park might be a fine way to clean up the eyesore, but nay-sayers objected to the rock formation as 'bald and unpicturesque.'"

- quoted by C.R. Roseberry, 1982

Location and Access

Central Park is located on Manhattan Island, in New York City, in southeastern New York State (Fig. 1). It is a long rectangle, 2.5 miles (4km) long and 0.5 miles (0.8km) wide, trending N29°E. Its long sides are Central Park West on the west and 5th Ave. on the east. The short ends are 110th St. on the north and 59th St. on the south (Fig. 2). The Park is easily reached by city streets and sidewalks, the subway, and bus routes on the major adjacent roads. Parking, however, can be a problem.

The site for Central Park was selected in 1853, when the New York State legislature passed a bill allowing the city to take over the rocky, unarable land in central Manhattan as the site for a park. In April, 1858 Frederick Law Olmsted and Calvert Vaux were awarded the design of the Park based on the 'Greensward' plan they submitted to a public competition sponsored by the Board of Commissioners of the Central Park. The original plans called for the northern boundary to be at 106th St., but in 1859 the land between 106th St. and 110th St. was added since it consists mainly of "a ledge of rocks" and it is "logically a part of the Park." (Olmsted, 1928, p.52, Document no. 16 relating to Central Park).

Topography and Drainage

The topography and drainage of the Park have been considerably influenced by the landscaping which began in 1858 and continues today. The southern four-fifths of the Park is characterized by gentle, rolling topography and flat meadows. The low point is 25 feet (7.6m) above sea level, along the shoreline of The Pond at the southeast corner, which was built from "ground which is low, and somewhat swampy" (Beveridge and Schuyler, 1983, p.127, referring to Olmsted and Vaux's 1858 Greensward Plan).

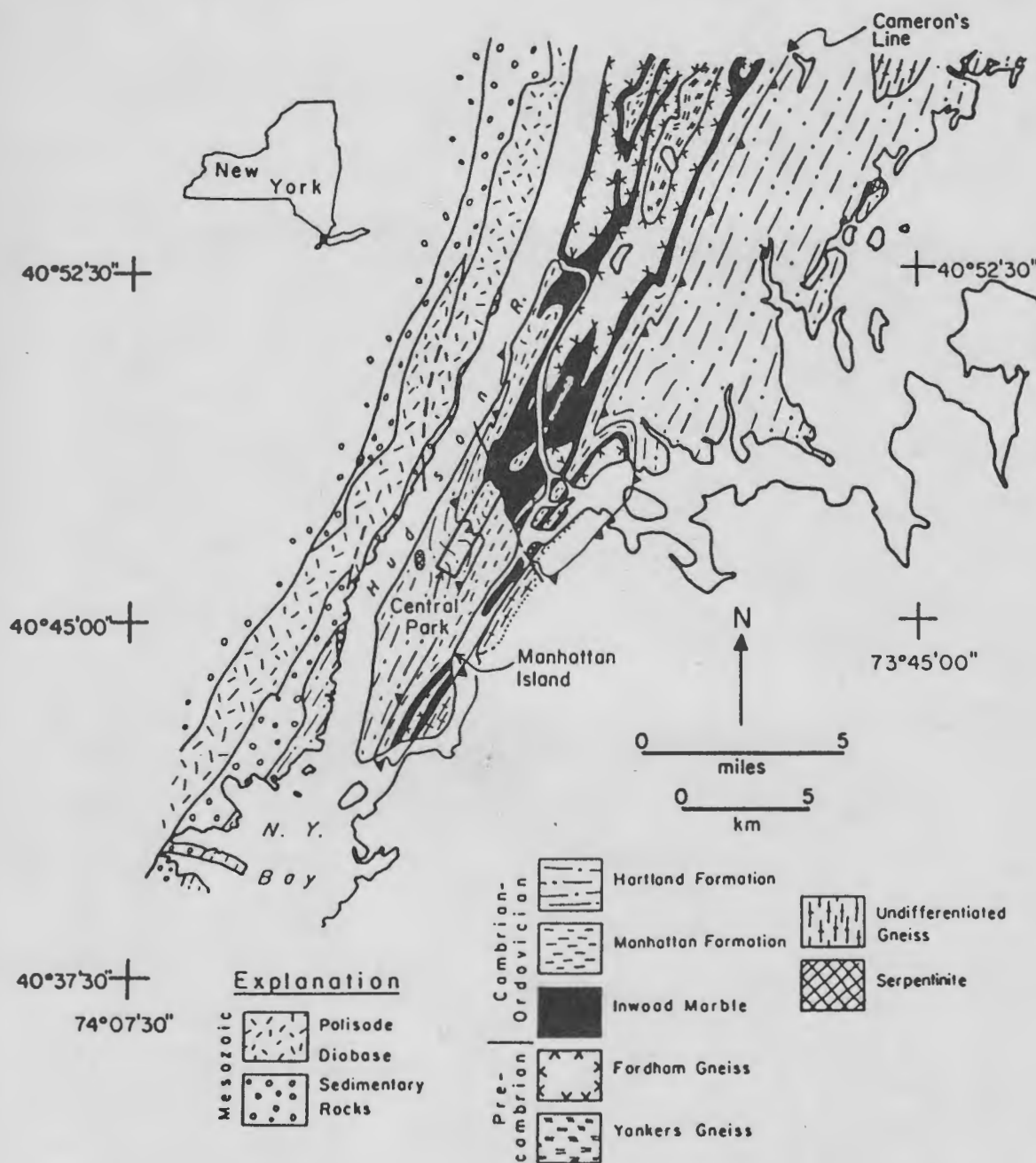


Figure 1. Regional geologic and location map for the New York City area. Geology is based on Fisher and others (1970), Merguerian and Baskerville (1986), and this study. Teeth are drawn on the upper plate of Cameron's Line thrust fault.

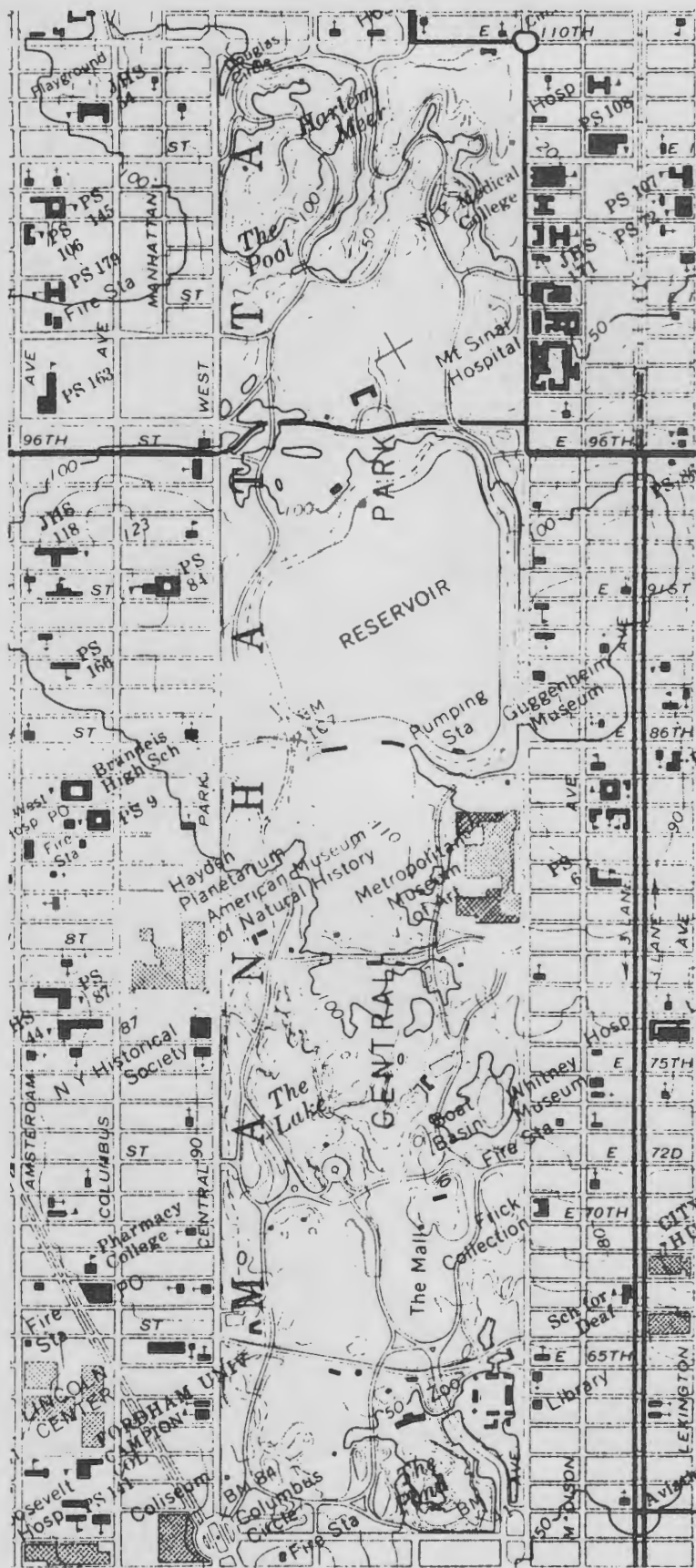
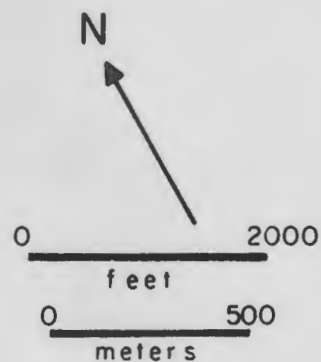


Figure 2. Central Park and surrounding streets, enlarged from the 7.5' Central Park, New York - New Jersey quadrangle (1:24,000, U.S.G.S., 1979). Contour interval is 10 feet.



Elevation rises to 110 feet (33.5m) around Belvedere Castle and the Great Lawn (Plate 1), an area that was originally a reservoir but was drained in 1929. The artificial modification of topography and drainage has involved not only the filling of swamps and the building of lakes, but also the installation of 95 miles of drainage pipe beneath the surface of the Park (Simpson and Hern, 1981).

The northern one-fifth of the Park, from about 100th St. to 110th St., is more rugged and has been left more or less in a 'natural state.' Relief is more pronounced here, rising from the Park's lowest point at 15 feet (4.5m) along the shore of the man-made Harlem Meer to the highest point at 130 feet (40m) atop the Great Hill. In their Greensward Plan of 1858 Olmsted and Vaux stated that the character of the "upper park...is the highest ideal that can be aimed at" and should be interfered with as little as possible (Beveridge and Schuyler, 1983, p.119).

Regional Geology

Manhattan Island is situated in the Manhattan Prong, a geologic region of metamorphosed Paleozoic marine sedimentary rocks overlying a billion-year-old basement gneiss complex. Most of the island's surface outcrop is schist which forms rolling hills and rocky bluffs. In the northeast and southeast parts of the Island the geologic map (Fig. 1) shows basement gneiss and the overlying Inwood Marble, which generally forms topographic lows.

The depth to bedrock on the island plays a crucial role in the construction of large buildings. Bedrock is at or near the surface around midtown and at the southern tip of Manhattan, providing a solid foundation for the clusters of skyscrapers which are built there. In between these areas bedrock is deeply buried and the skyline shows a corresponding drop in the height of buildings.

Northwest of the Manhattan Prong are the Hudson Highlands, a northeast-trending belt of Precambrian basement gneisses as old as 1,150 m.y. (Long and Kulp, 1962).

West of Manhattan, in New Jersey, the brown cliffs of the Palisades rise above the western shore of the Hudson River. The Palisades are formed from a diabase sill of Jurassic age which intrudes into the Upper Triassic-Lower Jurassic sedimentary rocks of the Newark Basin. Fossils found in the Newark Basin red beds include the remains of

reptiles, coelocanths, and freshwater brachiopods, as well as numerous dinosaur tracks (Schuberth, 1968).

East of Manhattan in Queens, Brooklyn, and Long Island the rocks of the Appalachians are covered by glacial drift and the Cretaceous-Tertiary sediments of the Atlantic Coastal Plain.

Previous Work

The name Manhattan Schist was proposed by Merrill (1890, 1896) for the schistose rocks which overlie the "Inwood Limestone" (1890, p.390) in southeastern New York. For almost 70 years after Merrill geologists working in the Manhattan Prong continued to use the term "Manhattan Schist" for what was believed to represent a continuous depositional sequence. Fettke (1914) recognized the variability of the formation and Berkey (1910) distinguished three members but did not map them separately.

Prucha (1956, p.672) considered the term "Manhattan Schist" inappropriate since "much of the formation is not schist" and proposed the name "New York City group" to include the entire Late Precambrian-Paleozoic basement-cover sequence south of the Hudson Highlands. Hall (1968a, 1976) demonstrated that the "New York City group" of Prucha contains two major unconformities as well as major premetamorphic thrust faults and is thus not a continuous depositional sequence.

Hall refined the stratigraphy, subdividing the Manhattan Schist into three subunits based on his mapping in the White Plains-Glenville area. He identified a lower schist unit, Member A; an overlying amphibolite layer, Member B; and an upper schist unit, Member C. Hall (1968b, 1976) proposed regional correlations of these subunits with rocks in New England. Manhattan A is believed to correlate with the Middle Ordovician Walloomsac Formation, and Members B and C are believed to correlate with the Eocambrian-Cambrian Hoosac and Waramaug Formations. Based on these correlations, Hall (1968b, 1976) made an analogy to the stratigraphy and structure worked out by Zen (1961, 1967) in the Taconic region of eastern New York and western Vermont, proposing a major thrust fault above Member A of the Manhattan Schist. This fault is equivalent to the Giddings Brook thrust and is the surface along which the older Members B and C were thrust westward above Member A. If this interpretation is correct, then the A, B, and C nomenclature for the Manhattan Schist is awkward, given that the autochthonous Member A is younger than the

allochthonous Members B and C. In Hall's report on the White Plains quadrangle (in press), the name Walloomsac Schist is used for the autochthonous Middle Ordovician rocks (previously Manhattan A), and the name Manhattan Formation is reserved for the allochthonous Cambrian rocks (previously Manhattan B and C).

Work on Manhattan Island by Mose and Merguerian (1985) and Merguerian and Baskerville (1986) resulted in recognition of three units within the Manhattan Schist of Merrill (1890), referred to as the lower, middle, and upper parts of Merrill's Manhattan Schist. The lower part correlates with the Walloomsac Formation of Hall (in press); the middle part correlates with the Manhattan Formation of Hall (in press); and the upper part with the Hartland Formation. The last is a variable package of rocks of Cambrian through Ordovician age which is believed to have been deposited on oceanic crust to the east of North America and then to have been thrust westward over the Manhattan Formation and other rocks along Cameron's Line (Rodgers, 1970; Merguerian, 1983a; Spinek and Hall, 1985).

Purpose of Study

The purpose of this study was to determine the extent and the nature of the stratigraphic units within the Park, and to use this information to observe the geologic relations along Cameron's Line. The abundant outcrop in Central Park and the 1:1,200 base maps that are available make it an ideal location to carry out detailed structural geologic mapping.

Methods of Study

Approximately five months of field work was completed during the summers of 1985 and 1986. The northwest corner of the Park was mapped during March, 1986. Mapping was done at a scale of 1"=100' (1:1,200) on a planimetric base provided by the Central Park Conservancy. It may or may not be a coincidence that the original competition for the design of Central Park in 1857 called for plans at this same scale. My field assistant, Steve Reich, and I drew the outcrops on the base map using pace and compass techniques. For each outcrop form lines of bedding (or subparallel early foliation) and other structural features were mapped. These form lines and stratigraphic contacts were connected between outcrops to produce the map pattern shown on Plate 1. 1,533 planar structural features and 1,160 linear structural features were measured in the field and plotted on equal-area diagrams using Netplot, a

computer program written by myself and Prof. Donald U. Wise. Vector mean orientations of structural features were calculated using a modified version of a program written by L. Scott Hills.

Approximately 60 oriented samples were collected for thin section preparation. To determine the opaque mineralogy, nine polished sections were prepared and observed under reflected light. Textural relations observed in thin section were used to determine the metamorphic environment and its relationship to the structural history. Extreme care was taken to assure that there was little or no aesthetic damage to the outcrops where it was necessary to sample.

Because of the shape of Central Park and the large-scale maps produced by this study, it was necessary to break the geologic map (Plate 1) into four parts for publishing. The map is published in two sheets, with each sheet consisting of two sections of the Park side by side. Figure 3 is a generalized geologic map of Central Park which is helpful to use in conjunction with Plate 1.

Acknowledgements

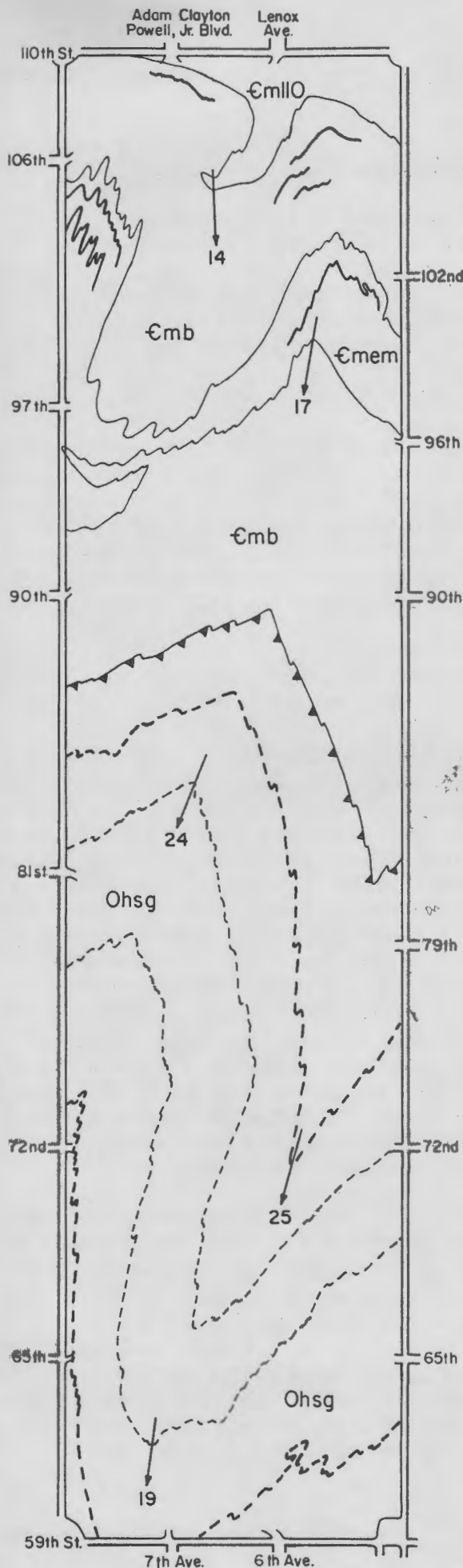
I would like to express my gratitude to Leo Hall for suggesting this project to me. I hope that this thesis will provide further understanding of the complex geology that his work has been so important in unravelling. The enthusiasm of Peter Robinson has been inspirational, and I thank him for stepping in to serve as my adviser and helping me complete this project. Donald Wise and Howard Jaffe reviewed the manuscript, and Tom Spinek, Peter Pannish, Charles Merguerian, John Bursnall, and David Elbert offered valuable criticism and advice in the field. Steve Field and Stephen Haggerty helped in identifying and understanding the opaque mineralogy. Steve Reich has my sincere thanks for assisting during my first summer of field work and mapping the outlines of most of the rock outcrops in the Park. The Central Park Conservancy and the Parks Department provided base maps and access to the Park.

My thanks to Erica and the (hydro)geologists of 106 North Whitney Street, my brother Jim, Jon and Phil, the Sleeper, William's Chicken, and the New York Mets. I am especially grateful to my grandmother Blanche Taterka for the two summers I spent with her, and to my mother and father for all of their encouragement and support.

Figure 3.

GENERALIZED GEOLOGIC MAP OF CENTRAL PARK, N.Y.

Bruce Talerko, 1987



EXPLANATION

Hartland Formation

Ohsg Schist and Granulite Member

Manhattan Formation

Emb Blockhouse Member

Emem East Meadow Member
amphibolite

Emb Blockhouse Member
amphibolite

Em110 110th St. Member

▲▲▲▲ Cameron's Line Thrust Fault

— Contact

- - - Form line of bedding and
subparallel foliation

- - - Form line of amphibolite beds

25 ↗ Trend and plunge of major
fold axes

0 2000
feet

0 400
meters

STRATIGRAPHY

. . . the writer concludes that if this group is pre-Cambrian, its identity as such has been obscured by a series of stratigraphic vicissitudes so complicated that it is beyond his powers, at present, to conceive them.

- Merrill (1890, p.391)

INTRODUCTION

The bedrock in Central Park consists of metamorphosed sedimentary and volcanic rocks. These rocks were deposited during Eocambrian through Ordovician time in a marine environment near the eastern continental margin of North America, fronting on the Iapetus Ocean. As this ocean basin closed during the Ordovician Taconian orogeny, the rocks were subjected to thrust faulting, folding, and metamorphism.

The tectono-stratigraphic column for the New York City area (Fig. 4a) is a result of a complicated series of depositional and tectonic events. At the bottom of the column is a basement gneiss complex which consists of the Fordham Gneiss and Yonkers Gneiss. The Precambrian Fordham Gneiss has been zircon dated at approximately 980 m.a. (Grauert and Hall, 1973). The Yonkers Gneiss has been dated at about 600 m.a. and may represent a former granitic intrusion into the Fordham Gneiss (Grauert and Hall, 1973). The basement is unconformably overlain by a marine shelf sequence consisting of the discontinuous Eocambrian-Cambrian Lowerre Quartzite below the Cambrian-Ordovician Inwood Marble (Hall, 1968a, 1976). The Walloomsac Schist, which is the flysch of the Taconian orogeny, unconformably overlies the Inwood Marble and marks the top of the autochthonous section. The allochthonous rock units above the Walloomsac Schist are the Eocambrian-Cambrian Manhattan Formation, which is made up of schist and amphibolite, and the Cambrian-Ordovician Hartland Formation, which consists of schist, granulite, gneiss, and amphibolite.

The Manhattan Formation is considered to be a distal facies of the Lowerre Quartzite which was deposited on the continental slope-rise of North America (Hall and Robinson, 1982). During the early stages of Taconian orogeny the Manhattan Formation was thrust westward over the autochthonous Walloomsac Schist along the Elmsford thrust (Hall, in press). The Hartland Formation is believed to have been deposited on oceanic crust to the east of the depositional site of the Manhattan Formation (Hall and Robinson, 1982) and then thrust westward over the

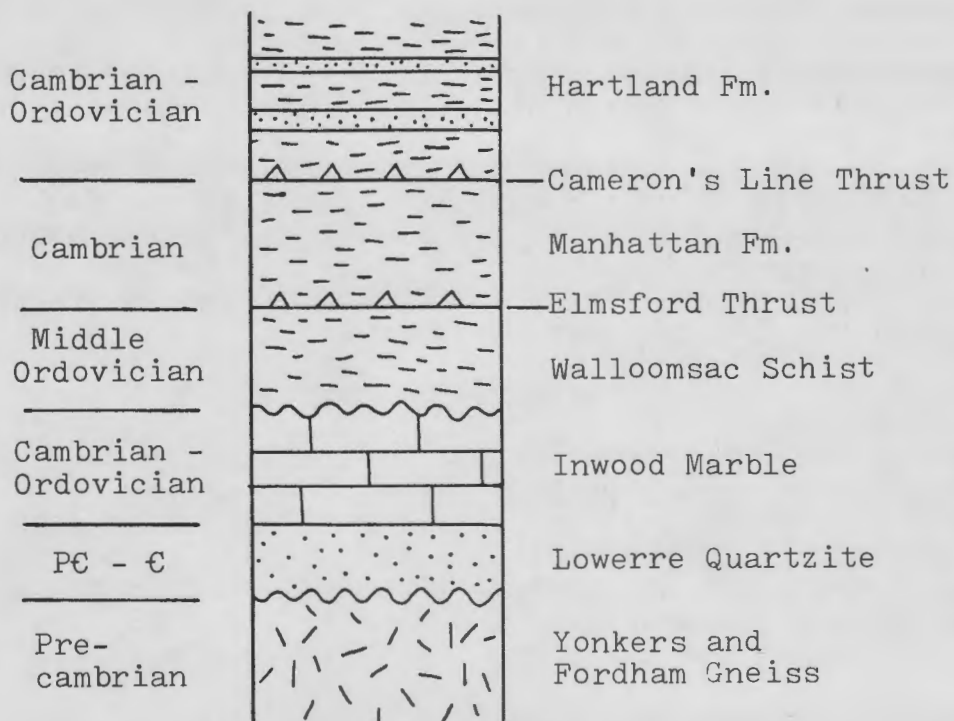


Figure 4a. Tectono-stratigraphic column for the New York City area based on Hall (in press).

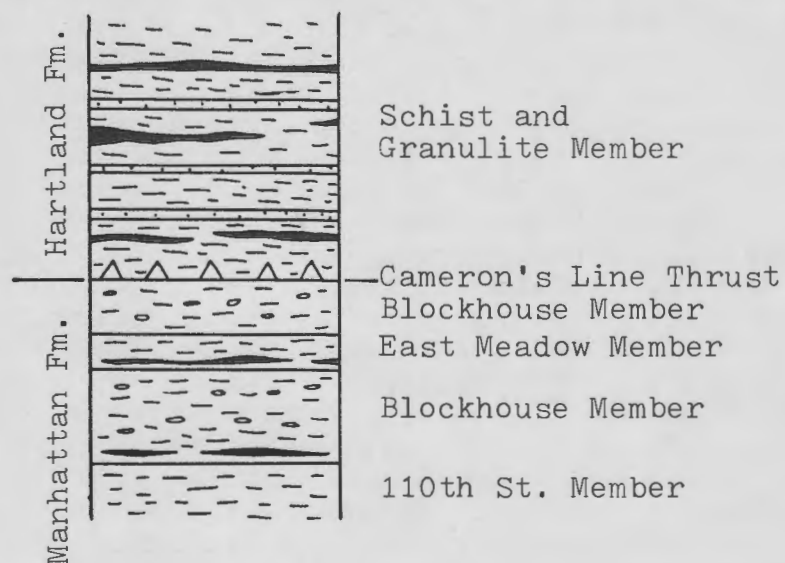


Figure 4b. Tectono-stratigraphic column for Central Park showing informal subunits of the Manhattan Formation. Amphibolite layers are shown in black.

allochthonous and autochthonous rocks along Cameron's Line. Cameron's Line has been shown to cut down into the stratigraphic column, juxtaposing the Hartland Formation with all of the rock units down to the basement (Merguerian, 1986).

In this study I have determined that the bedrock in Central Park consists of the Manhattan Formation and parts of the Hartland Formation. I am using the terminology of Hall (in press), with my own names for informal members within the Manhattan Formation.

MANHATTAN FORMATION

Three subunits of aluminous schist with rare interbedded granulite layers have been mapped within the Manhattan Formation. In two of the subunits there are interbedded layers of black amphibolite. In the following section the subunits are described in what is believed to be bottom-to-top order. The amphibolite beds, which are identical in the different subunits, are described last.

Distribution and Description of Subunits

110th St. Member. The 110th St. Member is exposed locally along the northern border of the Park. This rock is a brown- to reddish-brown-weathering garnet schist dominated by quartz, biotite, muscovite, and unzoned plagioclase (An₂₀₋₃₀, Table 1). Unlike the overlying Blockhouse Member, this unit is not magnetic in outcrop. Segregation layering is well developed with 3-6mm quartz-feldspar layers alternating with micaceous layers. Garnet is as large as 1cm in diameter in outcrops along the south side of the Harlem Meer. This garnet is roughly equant but heavily cracked and embayed. Inclusions of quartz, ilmenite, biotite, muscovite, apatite and zircon are abundant. Typical garnet at other outcrops is 1-3mm in size and exhibits similar texture. Fine-grained, subhedral kyanite and staurolite are present and appear to be in equilibrium with garnet. Staurolite is golden yellow in color and inclusion free. Biotite is pale yellow in the X direction and reddish-brown in the Y=Z direction. This reddish-brown color is distinct from the very dark brown color seen in the biotite in the other rock units in the Park. Pale brown to black pleochroic halos around zircon inclusions are striking and also give this biotite a distinctive appearance. In sample CP38 (Table 1) opaque minerals were observed under reflected light. The opaque mineral in the matrix is ilmenite with very minor hematite exsolution. Extremely fine-grained inclusions of

pyrrhotite were observed in trace amounts within kyanite grains.

Table 1. Estimated modes of samples from the 110th St. Member of the Manhattan Formation.

	E2-4b	CP33	CP38*	CP54
Quartz	33	33	39	58
Plagioclase	6	5	8	12
Mol.% An	(24)	(29)	(21)	(36)
Biotite	16	23	23	12
Muscovite	29	28	5	13
Kyanite	3	2	12	
Garnet	9	7	6	2
Staurolite	1	1		tr
Ilmenite	2	tr	4	3
Pyrrhotite			tr	
Apatite	1	tr	1	tr
Tourmaline ¹	tr		2	
Zircon	tr	tr	tr	tr
Total	100	100	100	100

* Opaque minerals observed in reflected light.

1. Tourmaline O = dark green; E = pale green.

Hand specimen descriptions and locations for Table 1.

E2-4b - Medium- to coarse-grained, brown-weathering, garnet schist. Collected from the north part of the outcrop on the promontory which sticks north into the Harlem Meer.

CP33 - Dark gray-weathering, coarse-grained, garnet schist. Garnet is up to 8mm in diameter. Collected at the same location as E2-4b.

CP38 - Brown-weathering, fine- to medium-grained, salt-and-pepper, garnet-biotite-kyanite schist. Collected north of the contact with the Blockhouse Member at the extreme north end of the large outcrop 560' (171m) S87W of the northwest corner of 110th st. and Lenox Ave.

CP54 - Medium-grained, light gray, feldspathic, garnet schist. Collected south of the contact with the Blockhouse member, 225' (68m) N70W of the south end of the Huddlestons Bridge.

Blockhouse Member. This rock type is exposed at the north end of the Park, with its southern contact with the East Meadow Member stretching from W.97th St. on the west

side to E.106th St. on the east side. It is typically a gray, medium-grained, garnet-magnetite-kyanite schist which weathers to a very distinctive knotty surface. The knots, or 'bootgrabbers', are the result of the positive weathering of 2-10cm pods of milky white, very fine-grained kyanite. Weathering color of the schist varies from light gray at clean outcrops to brown or brownish-gray at other outcrops. The rock consists predominantly of quartz, muscovite, biotite, and plagioclase, with lesser garnet, kyanite, and magnetite (Table 2). Hand specimens and outcrops of the Blockhouse Member strongly attract a hand magnet. Black tourmaline and sillimanite are locally present, and traces of clean subhedral staurolite are observed in thin section.

Fine-grained quartzose granulite layers with minor biotite and garnet are rarely found in this unit. A strong foliation is defined by the segregation of 2-5mm mica-rich layers and granular layers of similar thickness. In mica-rich segregation layers individual mica grains are oriented parallel to the foliation. Quartz grains are up to 5mm in size and always show undulose extinction. Grain shape is equant to elongate with long axes parallel to the dominant foliation. Plagioclase is generally equant and anhedral, and ranges in composition from An_{20} to An_{30} , with zoning very weak or absent. Polysynthetic twins are commonly bent, especially near grain boundaries.

Garnet is red in hand specimen and pink to very pale pink in thin section, with color zoning visible in some grains. Size varies from less than 1mm to 15mm. The bulk of the garnet was produced during the first phase of metamorphism and is embayed, deformed, and inclusion rich, with first-phase foliation wrapping around grains. Late garnet is locally present as subhedral, generally inclusion-free grains less than 1mm in size. Biotite is dark brown to almost black in the Y=Z direction, with abundant pleochroic halos around zircon inclusions. In some samples muscovite displays a weak pleochroism with Y=Z = very pale brown and X = colorless. This pale brown color may be due to an increased amount of Fe^{3+} (Deer, Howie, and Zussman, 1966). Fe-chlorite is locally present from the alteration of biotite and garnet.

Kyanite grains are commonly less than 1mm in size, making hand specimen identification of kyanite very difficult. Indeed, during my first summer of field work I was under the assumption that my boots were being grabbed by sillimanite nodules. In thin section kyanite grains are both scattered throughout the rock matrix and concentrated in pockets and lenses made up mostly of kyanite, with

Table 2. Estimated modes of samples from the Blockhouse Member of the Manhattan Formation.

	CP4*	CP4b	CP13	CP14	CP16	CP19	CP23
Quartz	35	38	69	38	45	47	56
Plagioclase	10	10	8	26	35	8	3
Mol.% An	(30)	(30)	(28)	(24)	(25)	(29)	(24)
Biotite	18	20	22	12	5	15	18
Muscovite	16	16	tr	13	2	15	15
Kyanite	9	9		7	2	7	3
Garnet	6	2	1	2	1	5	2
Sillimanite					8		
Fibrolite ¹				tr		tr	tr
Staurolite	tr	1					
Magnetite	3.5	3	tr	2	1	2	3
Ilmeno- hematite	1.5						
Hemo- ilmenite	tr						
Pyrite	tr						
Apatite	1	1	tr	tr	1	1	tr
Zircon	tr	tr	tr	tr	tr	tr	tr
Tourmaline					tr		
Total	100	100	100	100	100	100	100

	CP23	CP29	CP32	CP36	CP37*	CP55	W1-2a ²
Quartz	56	24	32	34	33	27	3
Plagioclase	3	5	13	9	7	11	tr
Mol.% An	(24)	(23)	(27)	(26)	(20)	(28)	
Biotite	18	25	21	18 ³	17	15	2
Muscovite	15	25	14 ⁴	21	19	15	7
Kyanite	3	10	11	8	8	17	87
Garnet	2	7	4	4	7	6	
Fibrolite ¹	tr						
Staurolite			tr	3	4		
Magnetite	3	3	4	3	4	8	1
Ilmeno- hematite					tr		
Apatite	tr	tr	tr	tr	1	1	tr
Zircon	tr	tr	tr	tr	tr	tr	tr
Tourmaline		1	1				
Total	100	100	100	100	100	100	100

* Opaque minerals observed in reflected light.

1. Fibrolite in CP14 and CP19 only occurs within muscovite. Fibrolite in CP23 occurs both within muscovite and in kyanite swarms.
2. Specimen W1-2a is from a large kyanite nodule.

3. Biotite X = pale yellow; Y=Z = red-brown.
4. Muscovite X = colorless; Y=Z = very pale brown.

Hand specimen descriptions and locations for Table 2.

CP4, CP4b - Slightly knotty, orangish-tan-weathering, medium-grained, gray, garnet-kyanite schist. Collected on the west side of the large outcrop 550' (168m) N50W of the north end of the Lasker Rink.

CP13 - Rusty-weathering, fine- to medium-grained, salt-and-pepper, quartzofeldspathic, biotite-garnet schist. Collected at the northeasternmost of the three outcrops immediately adjacent to the W.96th St. playground.

CP14 - Gray-weathering, medium-grained, gray, feldspathic, garnet schist. Same location as CP13.

CP16 - Medium-grained, strongly foliated, light gray, sillimanite-mica schist with coarse plagioclase, muscovite, and magnetite. Collected at the roadcut on the south side of the W.97th St. transverse 25' (8m) east of the east side of the Park Drive South overpass.

CP19 - Fine- to medium-grained, gray, quartzose, garnet schist. Collected on the east side of the large, steep outcrop 500' (152m) N50W of the northeast corner of 5th Ave. and E.103rd St.

CP23 - Gray-weathering, medium-grained, gray, quartzofeldspathic schist with well developed segregation layering. Large (5mm) muscovite grains are aligned in the foliation. Collected at the north end of the large outcrop on the southeast corner of the Harlem Meer.

CP29 - Medium-grained, salt-and-pepper, garnet-magnetite schist. Collected from the blasted outcrop above the wall along the east side of the W.96th St. entrance to the 97th St. transverse. This is the same outcrop at which the giant sillimanite crystal is observed (see METAMORPHISM).

CP32 - Knotty, brown-weathering, medium-grained, garnet-magnetite schist with minor black tourmaline. Red garnets are up to 1cm in diameter. Collected at the pavement outcrop 550' (168m) N44W of where E.102nd St. joins Park Drive North.

CP36 - Medium-grained, rusty-weathering, fissile, dark brown, garnet-magnetite schist. Collected at the outcrop on the west side of the W.106th St. exit from Park Drive

South, 150' (46m) N90E of the northeast corner of Central Park West and W.106th St.

CP37 - Medium-grained, brown-weathering, garnet-magnetite schist. Same locality as CP36.

CP55 - Fine- to medium-grained, knotty, grayish-brown-weathering, garnet-kyanite-magnetite schist. Collected at the south end of the long outcrop 200' (61m) N45W of the Huddlestone Bridge.

W1-2a - Very fine-grained, greenish-gray-weathering, milky white kyanite nodule. Collected at the long outcrop 600' (183m) S75W of the northwest corner of Lenox Ave. and 110th St.

lesser muscovite, biotite, and quartz. Thin sections through large kyanite nodules contain up to 87% 1-2mm sized subhedral kyanite (sample W1-2a, Table 2).

Opaque minerals were studied under reflected light in samples CP4 and CP37 (Table 2). The dominant opaque is magnetite, which is subhedral, coarse grained, and shows very minor exsolution of ilmenite or gahnite. Less abundant are finer grains of ilmeno-hematite, which is a two-phase grain consisting of ilmenite lamellae enclosed in a hematite host (Rumble, 1976). Grains of hemo-ilmenite, which is a two-phase grain consisting of hematite lamellae within an ilmenite host (Rumble, 1976), are less common but are observed coexisting with ilmeno-hematite. According to Rumble (1976) coexisting ilmeno-hematite and hemo-ilmenite are typical of pelitic schist in the garnet-staurolite and sillimanite zones. In some grains exsolution lamellae within exsolution lamellae are observed, indicating multiple generations of exsolution. In transmitted light magnetite can be differentiated from the ilmenite-hematite grains by the coarseness and euhedral shape of magnetite. Sample CP4 (Table 2) contains a trace of medium-grained, euhedral pyrite which is extensively weathered to goethite.

Accessory minerals include olive-green tourmaline, apatite, and fine zircon. Trace amounts of very fine red hematite and Fe-chlorite are present from the secondary alteration of Fe-bearing minerals.

The outcrop along Central Park West north of W.106th St. is fissile, rusty-brown-weathering and does not display the knotty texture typical of the Blockhouse Member. Thin sections of samples taken from this locality (CP36, CP37, Table 2) contain a dark reddish-brown biotite with striking

light brown to black pleochroic halos that are not seen in other Blockhouse specimens. Although this creates an overall appearance similar to the 110th St. Member, this locality may have been exposed to abnormal weathering caused by the numerous late faults which are observed here. Moreover, this rock contains abundant magnetite, supporting its assignment in the Blockhouse Member.

East Meadow Member. The East Meadow Member is mostly schist, with interbedded amphibolite layers of varying thickness. It is exposed on the hill north of the Pool, in the area around the 96th St. tennis courts, and in the East Meadow (Plate 1).

The simplest explanation of the stratigraphic position of the East Meadow Member is that it is a layer within the Blockhouse Member. However, alternative stratigraphic interpretations arise from various structural interpretations which are described in the next chapter.

This rock type is a medium-grained garnet-kyanite schist interbedded with granular schist layers which contain abundant 2-3mm grains of white plagioclase. Thinly bedded, fine-grained, quartzose granulite layers are observed locally. Weathering is characteristically light brown to reddish-brown in color with a smooth surface. The rock consists of quartz, plagioclase, biotite, and muscovite, with minor garnet and kyanite (Table 3). Sillimanite is present locally and hornblende is present in granular schist along amphibolite contacts (CP11, Table 3). Accessory minerals are apatite, zircon, and hemo-ilmenite, which was observed in reflected light in sample CP35 (Table 3). Secondary Fe-chlorite and hematite are present from the alteration of Fe-bearing minerals.

On the west side of the East Meadow (Plate 1) the rocks are gray- to tannish-gray-weathering and contain thin interbedded granulite layers, producing an overall appearance somewhat similar to the Schist and Granulite Member of the Hartland Formation. However, the proportion of interbedded granulite here is lower than in the rocks which have been mapped as Schist and Granulite south of the Reservoir, and the coarse muscovite which is abundant in the Schist and Granulite is not so prevalent in the rocks which crop out in the East Meadow.

Table 3. Estimated modes of samples from the East Meadow Member of the Manhattan Formation.

	CP10	CP11	CP31	CP34	CP35*
Quartz	72	55	52	43	62
Plagioclase	14	7	4	15	10
Mol.% An	(29)	(29)	(25)	(37)	(20)
Biotite	12	21	15	19	11
Muscovite			7	12	12
Kyanite			12	3	
Sillimanite			3 ¹		
Garnet	1		6	6	3
Magnetite		4			
Hemo-ilmenite	1		1	1	2
Hornblende		13 ²			
Apatite	tr	tr	tr	1	tr
Zircon	tr	tr	tr	tr	tr
Total	100	100	100	100	100

* Opaque minerals observed in reflected light.

1. Fibrolite occurs within muscovite grains; sillimanite occurs in folded sillimanite-quartz layers.
2. Specimen taken 5cm from an amphibolite bed.

Hand specimen descriptions and locations for Table 3.

CP10 - Gray-brown-weathering, fine-grained, gray, quartzofeldspathic granulite with minor biotite and garnet. Collected at the small round outcrop on the south side of path 400' (122m) S67E of the northwest corner of W.96th St. and Central Park West.

CP11 - Medium-grained, brown-weathering, salt-and-pepper, schistose, biotite-hornblende granulite. Collected at the outcrop north of the W.96th St. entrance to Park Drive South, 350' (107m) S60E of the northwest corner of W.96th St. and Central Park West. This outcrop is 20' (6m) south of the previous location.

CP31 - Medium-grained, brown-weathering, granular, garnet-kyanite schist. Collected along the Central Park West roadcut opposite W.104th St.

CP34 - Medium-grained, orangish-brown-weathering, quartzofeldspathic, biotite-garnet schist. A strong biotite lineation is developed on the foliation. Collected from the easternmost of the three outcrops on the north side of the 96th St. tennis courts.

CP35 - Brown-weathering, fine-grained, gray, schistose granulite with minor garnet. Collected along the west side of the bridle path, 160' (49m) S67W of where E.102nd St. joins Park Drive North.

Amphibolite. In the Blockhouse Member layers of black amphibolite crop out between Conservatory Garden and the Lasker Pool, and at the north side of the Great Hill across from the corner of 110th St. and Adam Clayton Powell, Jr. Boulevard (Plate 1). In the East Meadow Member 2- to 150-cm thick black amphibolite layers occur within several meters of the contact with the Blockhouse Member. The amphibolites in the East Meadow Member are identical to those observed in the Blockhouse Member.

The amphibolite is medium-grained, hornblende-plagioclase-epidote amphibolite with minor quartz, garnet, and biotite (Table 4). There is commonly a strong segregation layering in the amphibolite defined by thin, light-colored, feldspathic layers which are subparallel to bedding. Individual hornblende grains are aligned in the plane of foliation, defining a strong mineral lineation. In reflected light, opaque minerals in sample CP21 (Table 4) were observed to be mostly hemo-ilmenite. Trace amounts of pyrite with extensive alteration to goethite are also present.

Interbedded amphibolite layers vary in thickness from several centimeters to a meter or more and are discontinuous. Because these amphibolites are never observed cross-cutting sedimentary contacts they are believed to be volcanic in origin. They were probably deposited either as mafic lava flows or ash falls, although Blank (1972) proposed an origin as metamorphosed sedimentary calcareous-ferruginous beds.

Two outcrops on opposite sides of the North Meadow (Plate 1) have a 20cm layer of salt-and-pepper, fine-grained, feldspathic amphibolite which is distinctly lighter colored than the common amphibolites in the Park. It was not possible to sample this amphibolite for thin section study.

Table 4. Estimated modes of amphibolite samples from the Manhattan Formation. Specimens CP12, CP18, and CP21 are from the East Meadow Member; CP20 is from the Blockhouse Member.

	CP12	CP18	CP21*	CP20
Hornblende	57	53	34	37
Plagioclase	24	25	16	28
Mol. % An	(55)	(58)		
Quartz	15	20	22	13
Pistacite	1	1	11	19
Biotite	tr	1	13	
Sphene	1 ¹	tr ²		1 ³
Rutile		tr		tr
Hemo-ilmenite	2	tr	4	2
Pyrite			tr	
Apatite	tr	tr	tr	tr
Zircon	tr	tr	tr	
Total	100	100	100	100

* Opaque minerals observed in reflected light.

1. Occurs as rims on ilmenite grains.

2. Occurs as rims on ilmenite and rutile grains.

3. Occurs as rims on rutile.

Hand specimen descriptions and locations for Table 4.

CP12 - Black, massive, fine-grained, hornblende amphibolite. Collected at the outcrop north of the W.96th St. entrance to Park Drive South, 350' (107m) S60E of the northwest corner of W.96th St. and Central Park West.

CP18 - Fine-grained, black, hornblende amphibolite. Collected at the outcrop on the north side of path, 250' (76m) N50W of the northeast corner of 5th Ave. and E.101st St.

CP20 - Brown-weathering, fine-grained, green and white amphibolite. Collected along the west side of Park Drive North, 950' (290m) N60W of the northeast corner of 5th Ave. and E.105th St.

CP21 - Fine-grained, massive, brownish-black, hornblende-epidote-biotite amphibolite. Collected at the low outcrop on the south side of path, 475' (145m) S68E of the northwest corner of W.103rd St. and Central Park West.

Contacts

The contact between the Blockhouse Member and the 110th St. Member is subtle. This contact is well exposed at the north end of the outcrop on the promontory which sticks north into the Harlem Meer. Over a zone about 1m wide, medium-grained, knotty, magnetite-garnet schist of the Blockhouse Member grades into coarse-grained, smooth-textured, garnet schist of the 110th St. Member. Muscovite and garnet porphyroblasts in the 110th St. Member at this location are up to 8mm in diameter.

The knotty weathering texture of the Blockhouse Member is the main field distinction between it and the segregation-free, smooth-weathering East Meadow Member. This contact can be sharp, but more commonly the Blockhouse Member tends to become less knotty as it approaches the East Meadow Member and the contact appears to be gradational. The abundance of magnetite in the Blockhouse Member compared to its sparseness or absence in the East Meadow Member is helpful in placing this contact. The tan-to gray-weathering of the Blockhouse Member is usually distinct from the reddish-brown-weathering of the East Meadow Member.

This contact is particularly well exposed at the small outcrop 175 feet (53m) due south of the southeast corner of W.96th St. and Central Park West (Plate 1). At this location the knotty, magnetic Blockhouse Member is in sharp contact with the underlying smooth-weathering, non-magnetic East Meadow Member. Within the East Meadow Member a few feet from the contact there is a thin amphibolite bed. At the small, low outcrop 225 feet (69m) N20W of where E.102nd St. joins Park Drive North (Plate 1) the subtle difference in weathering color between the two units can be observed. The Blockhouse Member here is gray-weathering, somewhat magnetic, and very slightly knotty. The East Meadow Member is smoother, non-magnetic, and more reddish-brown in color. Although the difference between the two units is subtle, the contact is sharp enough to place a finger on.

The contact between the Blockhouse Member and the overlying Hartland Formation is not exposed. This contact is Cameron's Line, and is discussed below.

Age and Correlation

In southeastern New York, Hall (1976) has proposed regional correlations of the Manhattan Formation to the Waramaug Formation in western Connecticut (Gates and Martin, 1976; Merguerian, 1983) and to the Hoosac Formation

in western Massachusetts (Norton, 1976; Stanley and Ratcliffe, 1985). The Hoosac Formation also correlates with the Dalton Formation (Norton, 1976), which rests on basement on the west side of the Berkshire Massif. In the Taconics of western Vermont and eastern New York the equivalent of the Manhattan Formation is probably the Bull Formation, which contains fossils of the Early Cambrian trilobite Olenellus (Zen, 1967).

Based on these correlations the age of the Manhattan Formation is believed to be Eocambrian-Cambrian. This age is supported by Rb-Sr whole-rock age determinations of 555 ± 21 m.y. (Mose and Hall, 1979) and 554 ± 59 m.y. (Mose and Merguerian, 1985).

The rocks mapped here as the 110th St. Member are believed to make up the lowermost part of the Manhattan Formation. However, there is some similarity between the 110th St. Member and the Middle Ordovician Walloomsac Schist described by Hall (in press) in the White Plains area, specifically the brown-weathering color and the red biotite in thin section. An alternative correlation of the 110th St. Member with the Walloomsac Schist is supported by the position of the 110th St. Member below rocks which are undoubtedly Manhattan Formation' (i.e. Blockhouse Member) and above the contact with the Inwood Marble as reported in excavations on 110th St. (Charles Baskerville, pers. comm., 1987) and as shown on the geologic map of New York (Fisher and others, 1970). Hall (1968b, 1976) correlated the Walloomsac Schist to metamorphosed Middle Ordovician black shales of the Normanskill and Austin Glen Formations, which are believed to be the flysch of the Taconian orogeny. In western Vermont unmetamorphosed Normanskill rocks contain zone 12 and 13 graptolites, indicating a Middle Ordovician age (Zen, 1967). A correlation of the 110th St. Member with the Walloomsac Schist has important geologic implications which are discussed in the next chapter under the heading of "Alternative Structural Interpretations."

Derivation

The Manhattan Formation was deposited as a muddy sediment with rare thin sandy layers. These sediments were derived from North America and transported to a depositional site in the Iapetus Ocean on the continental slope-rise of North America during Eocambrian-Cambrian time (Hall and Robinson, 1982). Sedimentation was concurrent with the eruption of mafic volcanic rocks, either as lava flows or ash falls, producing the protolith for the interbedded schist and amphibolite that we see today. The Manhattan Formation is considered to be an eastern facies

of the Lowerre Quartzite (Hall and Robinson, 1982). The depositional setting was thus a deep water marine environment marginal to the North American continent. Clastic sediments were transported from the continent with coarse material deposited near shore as the Lowerre and finer material being carried farther oceanward to the depositional site of the Manhattan Formation rocks.

The source of the kyanite nodules is unknown. One possibility is that they represent primary aluminous concentrations which have been metamorphosed. Conversely, if the protolith for the Blockhouse Member was a homogenous shale, the nodules must have been produced by metamorphic processes. This is discussed further in the section on metamorphism.

HARTLAND FORMATION, SCHIST AND GRANULITE MEMBER

In western Connecticut and southeastern New York the Hartland Formation consists of gneiss, metamorphosed pelitic and granular rocks, and amphibolite. It has been locally subdivided by various workers (Gates and Martin, 1976; Hall, 1976; Stanley and Caldwell, 1976). The Hartland Formation rocks exposed in Central Park are part of the Schist and Granulite Member of Hall (1976), which consists of intimately interbedded schist and granulite, locally with mappable amphibolite beds.

Distribution and Description

Schist and granulite. This unit is well exposed south of the Reservoir to 59th St. (Plate 1). It is made up of gray-weathering, medium- to coarse-grained, muscovite-biotite-garnet schist with abundant interbedded fine-grained, gray- to tan-weathering, quartzose granulite. Granulite thickness varies from 1cm to more than 1m, with the overall schist:granulite ratio approximately 4:1 but at some outcrops as low as 1:1. Coarse muscovite plates up to 2cm abound in the schist, giving the rock a 'spangly' appearance in sunlight and contributing to the overall gray color. The everpresent interbedded granulite and coarse muscovite plates are the most distinguishing features of the Schist and Granulite Member.

The schistose beds display a strong segregation layering subparallel to bedding. In micaceous segregation layers mica grains are oriented parallel to the layering. Quartz grains in the granular layers are anhedral and elongate with their long dimensions parallel to the layering.

Biotite is very dark brown in the Y=Z direction and has pleochroic halos around zircon inclusions. Weakly pleochroic muscovite with Y=Z = very pale brown, X = colorless is observed in five of eighteen schist samples (Table 5). Kyanite grains less than 1mm long are scattered throughout the micaceous layers and in kyanite-rich pockets and lenses with minor muscovite, biotite, and quartz. Garnet is red in hand specimen. In thin section it is pink and riddled with fine inclusions of mostly ilmeno-hematite with lesser quartz, biotite, muscovite, plagioclase, and apatite. Garnet is typically ragged, anhedral and embayed, and some grains are elongate with long axes parallel to the foliation.

Most hand specimens of the Schist and Granulite Member are magnetic. In reflected light, opaque minerals in sample CP5 (Table 5) are dominantly coarse, subhedral magnetite. Ilmeno-hematite grains are observed in trace amounts in the rock matrix, and they are the only opaque mineral observed as inclusions within garnet porphyroblasts. Accessory minerals include apatite, zircon, and locally tourmaline. Traces of staurolite, fibrolite, and secondary hematite and Fe-chlorite are common.

The schistose beds within the unit are variable. Weathering texture is mostly smooth, but kyanite aggregates are present in the schist at some outcrops, producing a knotty-weathering texture identical to that seen in the Blockhouse Member of the Manhattan Formation. Knotty-weathering schist outcrops occur in the Ramble, in the area between W.81st St. and Belvedere Lake, and in the southwest corner of the Park, west of Heckscher Playground (Plate 1). These knotty-weathering schists are intimately interbedded with granulite and smooth-weathering schist. I was unable to follow them as separate mappable units, which leads me to believe that they are local facies emphasized by variable weathering.

North of Conservatory Pond, near E.76th St., the rocks are brown-weathering and slightly rusty with a smaller proportion of granulite. Thin sections from these outcrops are distinct for their abundant graphite, red-brown biotite, and relatively An-rich plagioclase (samples CP57, E9-8, Table 5). These rocks appear to make up a layer below the lowest of the four amphibolite horizons, but the lack of outcrop to the north and west makes it impossible to map the extent of this layer.

Granulite beds are tan- or gray-weathering, very fine-grained, and consist mainly of quartz and plagioclase

(Table 6). Very fine garnet, biotite, and muscovite are locally observed in outcrop.

Table 5. Estimated modes of schist samples from the Schist and Granulite Member of the Hartland Formation.

	CP1	CP5*	CP7	CP8	CP15
Quartz	44	67	32	60	35
Plagioclase	11	1	13	27	31
Mol.% An	(20)	(24)	(25)	(26)	(25)
Biotite	18	9	14	3	4
Muscovite	24 ¹	12	29	9 ¹	8
Kyanite		5	3		6
Garnet		1	2	tr	2
Magnetite		5	6	1	2
Ilmeno-hematite	2	tr			
Apatite	1	tr	1	tr	tr
Zircon	tr	tr	tr	tr	tr
Tourmaline		tr ²			
Fe-chlorite			tr	tr	12
Total	100	100	100	100	100

	CP24 knot	CP24 ³ matrix	CP28	CP30	CP40	CP42
Quartz	16	19	55	44	50	38
Plagioclase			8	3	9	12
Mol.% An			(26)			
Muscovite	3	37	13	23	21 ¹	25
Biotite	3	35	19	11		19
Kyanite	76	8	2	10		
Garnet	1	1	3	6	1.5	4
Fibrolite		tr ⁴	tr ⁵	tr ⁵		
Staurolite				tr		
Magnetite	tr	tr		3	4	2
Ilmeno-hematite			tr			
Apatite			tr	tr	tr	tr
Tourmaline	1 ²				1.5 ⁶	
Zircon	tr	tr	tr	tr	tr	tr
Fe-chlorite					13	tr
Total	100	100	100	100	100	100

Table 5. continued

	CP45	CP46	CP47	CP49	CP50	CP51
Quartz	24	51	37	51	50	4
Plagioclase	9	3	3	8	8	1
Mol.% An	(21)			(23)		
Muscovite	33 ¹	12	36	17 ¹	15	43
Biotite	30	11	9	15	12	34
Kyanite		17	1		7	
Garnet		4	9	5	6	7
Fibrolite			tr	tr		
Staurolite			4			1
Magnetite	3	2		4	2	6
Ilmeno-hematite			1			
Apatite	1	tr	tr	tr	tr	2
Zircon	tr	tr	tr	tr	tr	tr
Fe-chlorite						2
Total	100	100	100	100	100	100

	CP53	CP57*	E9-8	CP58a	CP58b
Quartz	45	40	44	51	50
Plagioclase	11	21	13	5	4
Mol.% An	(21)	(39)	(38)		
Biotite	16	15 ⁷	16 ⁷	14	12
Muscovite	19	16	15	13	10
Kyanite		2	3	10	17
Garnet	4	4	8	2	2
Magnetite	4			4	4
Graphite		2	1		
Pyrrhotite		tr			
Hematite		tr			
Rutile		tr			
Apatite	1	tr	tr	1	1
Tourmaline		tr		tr ⁶	
Zircon	tr	tr	tr	tr	tr
Total	100	100	100	100	100

Note - Fe-chlorite is retrograde.

* Opaque minerals observed in reflected light.

1. Muscovite X = colorless; Y=Z = very pale brown.

2. Tourmaline O = dark green; E = pale gray.

3. Specimen CP24 is a kyanite nodule in schist.

4. Fibrolite only observed within tourmaline.

5. Fibrolite only observed within muscovite.

6. Tourmaline O = dark green; E = light pink.

7. Biotite X = pale tan; Y=Z = very reddish, medium-brown.

Hand specimen descriptions and locations for Table 5.

CP1 - Gray-spangly-weathering, medium- to coarse-grained, quartzofeldspathic schist with strong segregation layering. Collected on the west side of Overlook Rock, 475' (145m) N40W of the northeast corner of E.61st St. and 5th Ave.

CP5 - Gray-weathering, medium-grained, tan, quartzose, garnet-muscovite schist. Collected at the south end of the large outcrop with a rustic shelter, 250' (76m) N35W of the northeast corner of E.67th St. and 5th Ave.

CP7 - Medium-grained, knotty, grayish-tan-weathering, feldspathic, garnet-kyanite schist. Foliation is overgrown by coarse (1cm) muscovite. Collected at the large outcrop in the southwest corner of the Ramble, 150' (46m) N50E of the north end of Bow Bridge.

CP8 - Medium- to coarse-grained, tan, quartzofeldspathic, muscovite-chlorite-biotite schist. Segregation layering is very well developed. Collected from the same location as CP7.

CP15 - Fine- to medium-grained, feldspathic, silvery-green, muscovite-biotite-chlorite schist. Collected at the outcrop on the west side of Park Drive South, 250' (76m) N40E of where the W.85th St. entrance joins Park Drive South.

CP24 - Gray-weathering, medium- to coarse-grained, gray, garnet-tourmaline-kyanite-mica schist. This sample contains a large (11x4cm) very fine-grained, greenish-white kyanite nodule which is aligned in the foliation and folded. Collected at the small outcrop on the north shore of the Lake, 310' (94m) N80E of the north end of Bow Bridge.

CP28 - Medium- to coarse-grained, light gray, spangly, muscovite-biotite-garnet schist. Segregation layering is well developed and is overgrown by coarse (1cm) muscovite plates. Collected on the east side of the outcrop 10' (3m) north of the Metropolitan Museum of Art.

CP30 - Dark gray, slightly knotty-weathering, garnet-kyanite schist. Collected at the south end of the long outcrop 300' (91m) S15W of the southwest corner of Belvedere Castle.

CP40 - Brown-weathering, medium-grained, greenish-tan, garnet schist in contact with a fine-grained, quartzofeldspathic granulite with minor biotite. Collected

at the westernmost of the two outcrops on the south side of Wollman Rink.

CP42 - Tan- to gray-weathering, spangly, medium-grained, quartzofeldspathic, muscovite-biotite-garnet schist. Collected during construction at the steep outcrop in the outdoor cage at the northwest corner of the Zoo.

CP45 - Gray-weathering, spangly, medium- to coarse-grained, tannish-gray schist. Collected at the outcrop at the south side of the Bird Sanctuary, 290' (88m) N55E of the northeast corner of 59th St. and 6th Ave.

CP46 - Medium-grained, gray-weathering, slightly knotty, garnet-kyanite schist. Collected at the outcrop on the south side of path, 730' (223m) S45E of the northeast corner of W.85th St. and Central Park West.

CP47 - Brown-weathering, medium-grained, gray-brown, garnet schist. Collected along the roadcut on Central Park West, 125' (38m) N90E of the northwest corner of W.85th St. and Central Park West.

CP49 - Medium-grained, reddish-brown, garnet schist with abundant coarse muscovite aligned in the foliation. Collected at the small outcrop in the northeast part of the Ramble, 530' (162m) S55W of the southwest corner of the Ramble parking lot.

CP50 - Medium- to fine-grained, reddish-tan, granular, garnet schist. Collected on the west side of the outcrop 50' (15m) east of the statue of King Jagiello.

CP51 - Gray-weathering, spangly, medium- to coarse-grained, feldspathic, muscovite-biotite-garnet schist. Abundant coarse muscovite. Collected on the west side of the large outcrop 475' (145m) N80E of the northwest corner of W.77th St. and Central Park West.

CP53 - Medium-grained, tannish-gray-weathering, feldspathic, muscovite-biotite schist. Collected at the roadcut on the north side of the 79th St. transverse, 50' (15m) west of the west side of the Park Drive North overpass.

CP57 - Medium-grained, grayish-rusty-brown-weathering, garnet-muscovite schist. Collected at the west side of the outcrop 400' (122m) S85W of the northeast corner of E.77th St. and 5th Ave.

CP58 - Medium-grained, tannish-gray-weathering, spangly, muscovite schist. Abundant coarse muscovite. Collected at the north end of the outcrop on the southwest corner of the small bridge over the bridge path, 540' (165m) S80E of the northeast corner of W.60th St. and Central Park West.

E9-8 - Fine- to medium-grained, brown-weathering, quartzofeldspathic, garnet-mica schist. Collected at the small, low outcrop next to the 5th Ave. wall, immediately south of the path running from the E.76th St. gate.

Table 6. Estimated modes of granulite samples from the Schist and Granulite Member of the Hartland Formation.

	CP2	CP6	CP9*	CP43
Quartz	70	70	83	71
Plagioclase	15	13	9	12
Mol.% An	(13)	(38)	(26)	
Biotite	15	6	4	7
Muscovite	tr	8	tr	6
Kyanite		tr		
Garnet		3	tr	
Hematite	tr	tr	4	4
Apatite	tr	tr	tr	tr
Zircon	tr	tr	tr	tr
Total	100	100	100	100

* Opaque minerals observed in reflected light.

Hand specimen descriptions and locations for Table 6.

CP2 - Tan-weathering, fine-grained, salt-and-pepper, quartz-feldspar-biotite granulite. Collected on the west side of Overlook Rock, 475' (145m) N40W of the northeast corner of E.61st St. and 5th Ave.

CP6 - Fine-grained, tan-weathering, quartz-feldspar-garnet granulite. Collected at the large outcrop on the east side of path, 440' (134m) S09E of the southwest corner of the Band Shell.

CP9 - Gray-weathering, fine-grained, gray, quartz-feldspar granulite with very minor biotite and red garnet. Collected from the south end of the group of outcrops around the rustic shelter, 375' (114m) N33E of the north end of Bow Bridge.

CP43 - Gray-weathering, fine-grained, gray, quartz-feldspar granulite. Collected at the south end of the Bird Sanctuary, 290' (88m) N55E of the northeast corner of 59th St. and 6th Ave.

Amphibolite. Medium-grained black amphibolite beds are interbedded in the Schist and Granulite Member. These beds consists mainly of green hornblende, plagioclase, and quartz (Table 7). Pistacite is present in varying amounts, and one sample contains green augite (sample CP25, Table 7). Garnet is commonly observed in amphibolite, especially along schist contacts. In reflected light, opaque minerals in CP48 (Table 7) are dominantly ilmenite with very minor hematite exsolution. Pyrite is present in trace amounts.

The character of these beds is identical to that of amphibolites in the Manhattan Formation. Several beds occur in zones several meters wide (Fig. 5), with pinch-and-swell structure and very tight folding that makes it difficult to follow individual beds from outcrop to outcrop. Some amphibolite outcrops contain segregation layering which outlines the structure. This consists of thin white quartzofeldspathic layers subparallel to bedding contacts between amphibolite and schist. This layering is interpreted to be of metamorphic origin because the light layers are always in sharp contact with the dark rock, and no graded bedding or sedimentary layering was observed in amphibolite beds.

Amphibolite zones occur at four levels in the Schist and Granulite Member (Plate 1). Zones 1 (lowest) and 4 (highest) can be followed across the folded structure of the Park, but zones 2 and 3 are apparently not continuous.

There are three possible explanations for the discontinuity of the amphibolite beds: 1) they may have been deposited as discontinuous lava flows or ash falls; 2) they may have been pulled apart during deformation and are now boudins; or 3) the ends of the layers may be first-phase fold hinges. The ends of beds shown in Figure 5 appear to have an obscure first-phase foliation cutting across them, but this is consistent with all three explanations above. Judging from the map pattern and the varying thickness of amphibolite beds, I believe that reasons 1 and 2 above are the most likely explanations for the discontinuities that are observed.

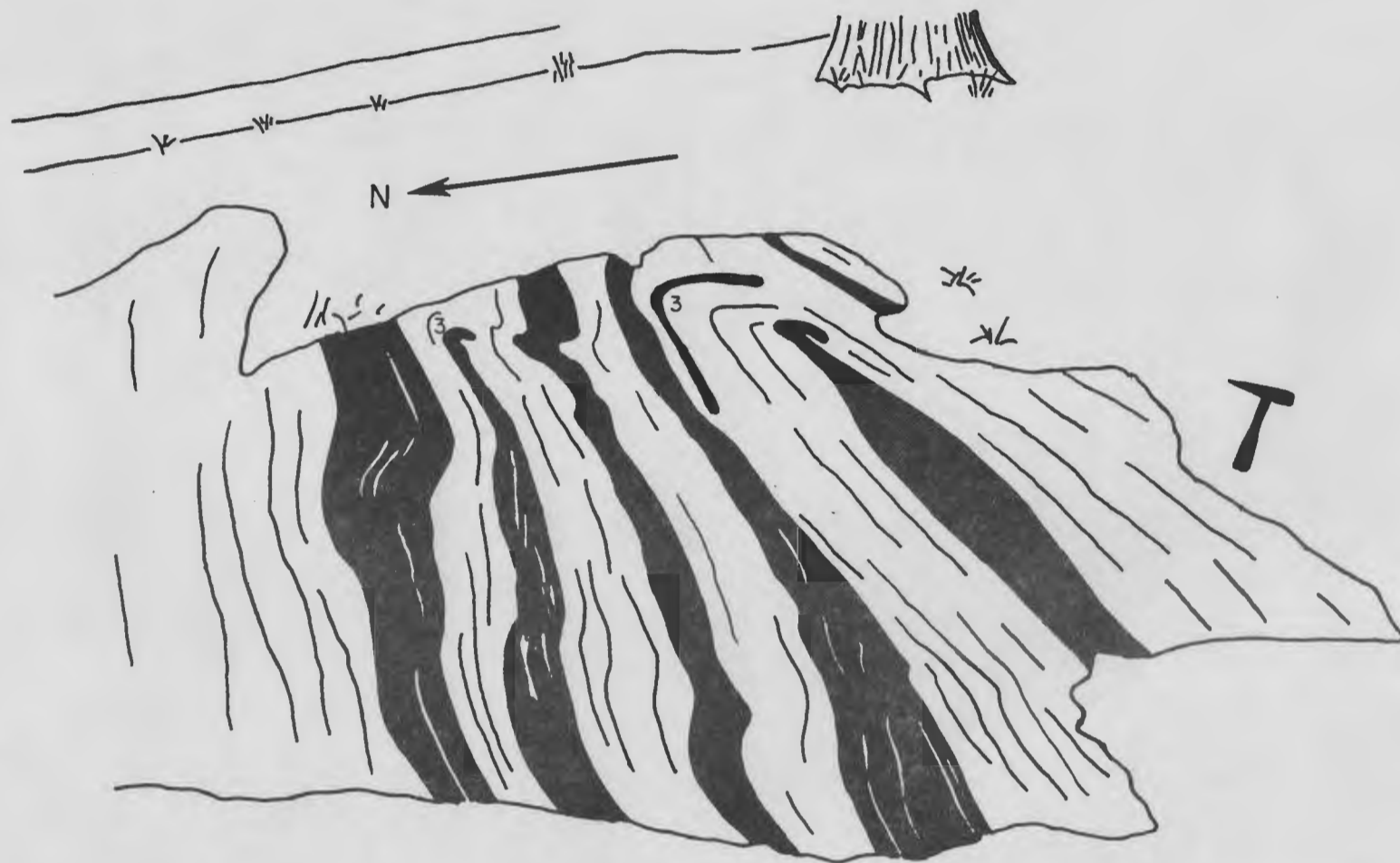


Figure 5. Sketch of pavement outcrop 1m east of the W.86th St. playground. Black amphibolite beds are interbedded with schist and are folded by third-phase folds (numbered.) Amphibolites exhibit pinch-and-swell structure and are discontinuous (see text for explanation.) Drawn from a photograph taken standing on top of the fence on the east side of the playground, looking east.

Table 7. Estimated modes of amphibolite samples from the Schist and Granulite Member of the Hartland Formation.

	CP25	CP41	CP44	CP48*	CP52
Hornblende	25	46	34	47	47
Plagioclase	32	37	34	22	27
Mol. % An	(58)	(45)	(27)	(56)	(58)
Quartz	15	14	17	28	22
Augite	17				
Pistacite	7	tr	14	1	1
Biotite			tr	tr	
Sphene	3	2	tr		2
Rutile	tr				
Ilmenite	1	tr	1	2	1
Pyrite				tr	
Apatite		1	tr	tr	tr
Zircon		tr	tr	tr	tr
Total	100	100	100	100	100

* Opaque minerals observed in reflected light.

Hand specimen descriptions and locations for Table 7.

CP25 - Black-weathering, massive, fine-grained, hornblende-pyroxene-epidote amphibolite. Collected from the bridle path cut, 175' (53m) S80E of the northwest corner of W.72nd St. and Central Park West.

CP41 - Dark-rusty-brown-weathering, medium-grained, slabby, salt-and-pepper, hornblende amphibolite. Collected at the easternmost of the two outcrops on the south side of the Wollman Rink.

CP44 - Brownish-black weathering, fine-grained, strongly foliated, greenish-black, hornblende-epidote amphibolite. Collected at the large outcrop on the west side of the Bird Sanctuary, 430' (131m) N25E of the northeast corner of 59th St. and 6th Ave.

CP48 - Fine-grained, massive, rusty-brown- to black-weathering, salt-and-pepper, hornblende amphibolite. Collected from the small outcrop in meadow, 75' (23m) S57W of the southwest corner of the Ramble parking lot.

CP52 - Fine-grained, massive, black amphibolite. Collected at the outcrop above the wall on the south side of the 79th St. transverse, 70' (21m) east of the east end of the Park Drive North overpass.

Age and Correlation

Hall (1976) correlated the Schist and Granulite Member in the White Plains area with similar rocks east of Cameron's Line in western Connecticut and western Massachusetts. These units include Hartland I in western Connecticut (Gates and Martin, 1976; Stanley and Caldwell, 1976; Scott, 1974); the Taine Mountain Formation in the Collinsville quadrangle (Stanley, 1964); and the Moretown Formation in western Massachusetts (Stanley and Ratcliffe, 1985). These workers agree on a Lower Middle Ordovician age for the Schist and Granulite Member and correlative rocks.

Derivation

The Schist and Granulite Member is characterized by centimeter- to meter-sized beds of rhythmically interlayered granulite and pelite. Graded bedding is locally observed in Schist and Granulite Member outcrops, suggesting that there was some deposition by turbidity flows. Sedimentation was mostly silt- and clay-sized material settling out of the water column, with coarser material periodically deposited by turbidity currents.

Stanley and Ratcliffe (1985) interpret the equivalent Moretown Formation to have been deposited on oceanic crust in a forearc basin to the east of an emergent Taconian non-volcanic accretionary wedge and to the west of the Bronson Hill volcanic arc complex. A source area on the North American continent is considered unlikely since age-equivalent rocks deposited to the west of the Moretown are deep water shales without any significant granular content. They conclude that there were two source areas, one in the emergent accretionary wedge situated between the depositional site of the Moretown Formation and the North American continent, and the other in the volcanic arc complex to the east. The proximity to the volcanic arc complex is supported by the commonly observed amphibolite beds in both the Moretown Formation and the Schist and Granulite Member of the Hartland Formation.

INTRUSIVE ROCKS

At least three distinct types of intrusive rocks occur in Central Park:

1) Early pegmatites. These are made up of coarse white to pinkish feldspar, quartz, and muscovite with minor tourmaline and/or magnetite. The size of these features can be as small as a single 2-3cm feldspar grain or as

large folded layers up to 10cm thick. The larger layers are parallel to bedding and are affected by all phases of deformation. The dominant foliation wraps around early pegmatites.

2) Late pegmatites. The texture and mineralogy of late pegmatites are the same as that of the early pegmatites. However, late pegmatites occur as irregular masses and snake-like dikes which cross-cut all ductile structural features.

3) Late granites. Late granites consist of white fine-grained quartz, feldspar, and muscovite with red garnet. They are the least abundant of the three intrusive rocks described here. They occur mainly as irregular cross-cutting dikes, and are commonly associated with late pegmatites.

When late pegmatites and granites occur together it is in a layered dike with an interior granite layer sandwiched between layers of pegmatite which are in contact with the surrounding schist. This configuration is not a typical chilled margin texture one would expect from an intrusive dike. However, the coarse-grained margins of the dikes may be caused by dewatering of the host schist. Hydration of the dike would lower the melting temperature of the granite and facilitate the ionic migration necessary to build coarse crystals.

METAMORPHIC QUARTZ VEINS

Quartz veins are 5-10cm thick and up to 2m in length. They are ubiquitous throughout the Park. Quartz is the main constituent, with fine-grained muscovite and coarse whitish-pink feldspar locally present. These veins are always aligned in the dominant foliation and show the effects of all deformational phases.

STRUCTURAL GEOLOGY

. . . many minor folds are developed in the schist, so that at times it becomes exceedingly contorted and crinkled.

- Fettke (1914, p.211)

INTRODUCTION

Two phases of early thrust faulting and three main phases of folding have affected the rocks in Central Park. Direct evidence of early thrust faulting was not found, but it is inferred based on stratigraphic relationships and the interpretations of other workers (Hall, 1980; Spinek and Hall, 1985). The overall geometry of the rocks in the Park is that of two large-scale recumbent fold phases folded by pervasive, upright, northeast-trending third-phase folds. Figure 6 shows the idealized geometrical relationships produced by these three phases of folding. First-phase isoclinal recumbent folds appear to have east-west-trending hinge lines (Fig. 6a). They are rarely observed, but their axial-plane foliation is ubiquitous. Second-phase folds are also isoclinal and recumbent, but these folds are reclined with gently southwest-plunging hinge lines (Fig. 6b, Fig. 7). Third-phase folds are the dominant fold set in the Park, folding all earlier structures (Fig. 6c). These upright northeast-trending folds have axes plunging gently southwest, coaxial with second-phase folds. Third-phase folds can be observed at almost every outcrop, and map-scale third-phase folds can be traced across the Park from southwest to northeast (Fig. 8).

Deformation younger than the third phase is relatively minor. The fourth phase is a north-south-trending, upright crenulation cleavage in third-phase axial-plane foliation which is developed in some outcrops at the southern end of the Park. The fifth phase is expressed as broad east-west-trending warps in third-phase axial surfaces which are visible in outcrop and in map pattern (Fig. 8).

For structural analysis, nine subareas were defined (Fig. 9). For the most part, subarea boundaries were drawn with respect to the axial surface traces of third-phase map-scale folds. In the northern part of the Park where the structure is more complicated, map features relating to second-phase folding and late warping were also used.

Geologic cross sections (Plate 2) were constructed by axial projection along third-phase fold axes. The average trend and plunge of third-phase fold axes for each subarea were calculated as the vector mean of all the measured fold

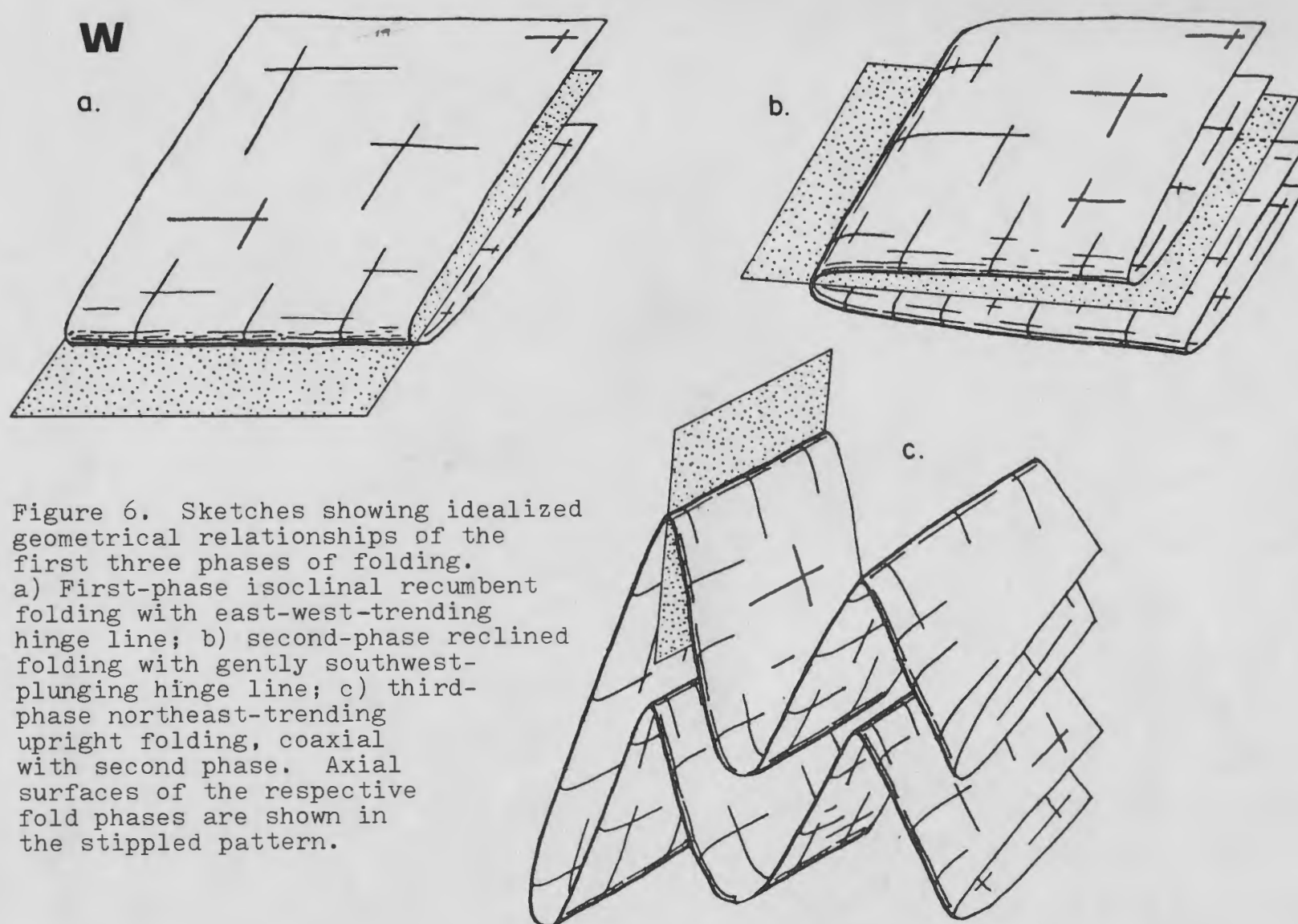


Figure 6. Sketches showing idealized geometrical relationships of the first three phases of folding. a) First-phase isoclinal recumbent folding with east-west-trending hinge line; b) second-phase reclined folding with gently southwest-plunging hinge line; c) third-phase northeast-trending upright folding, coaxial with second phase. Axial surfaces of the respective fold phases are shown in the stippled pattern.

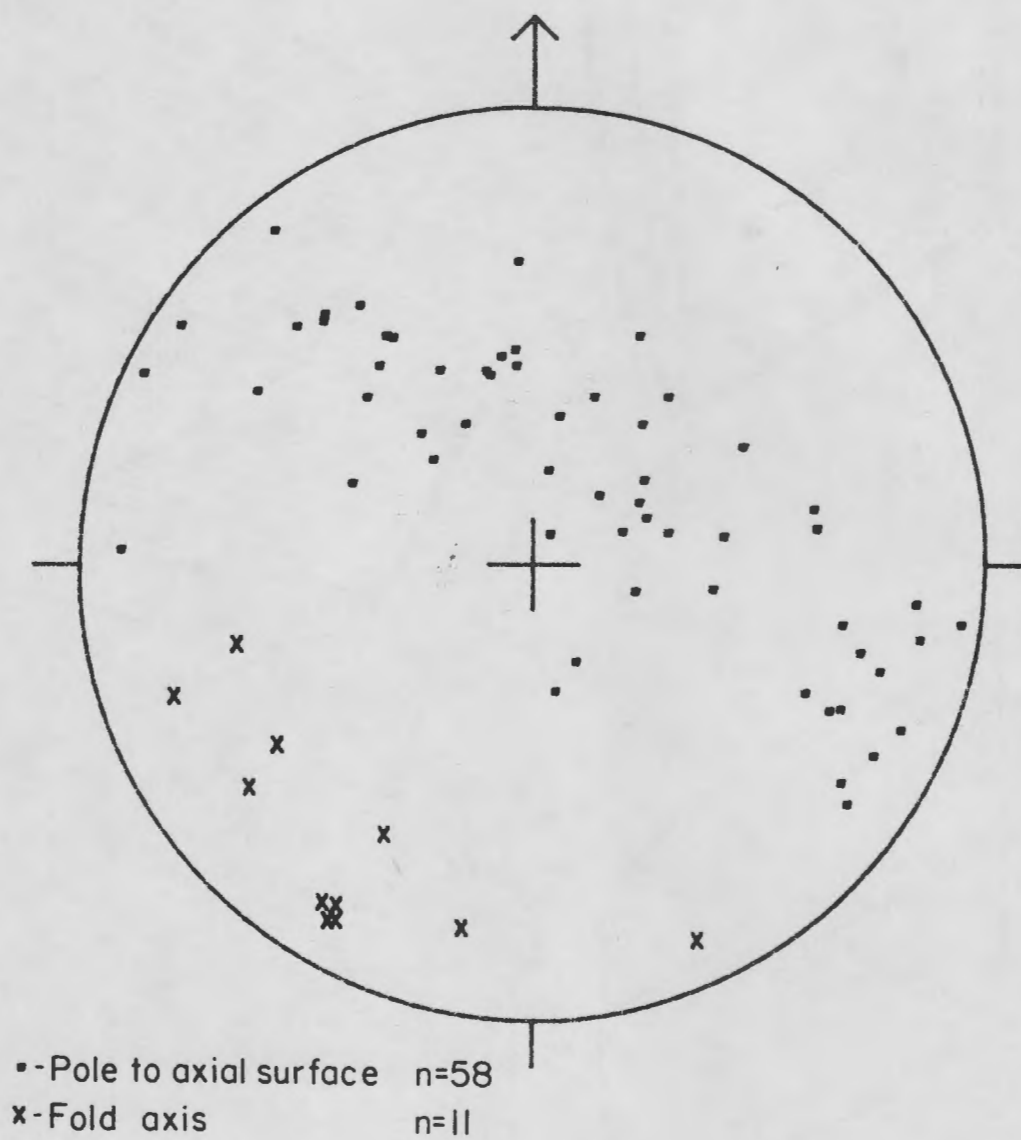
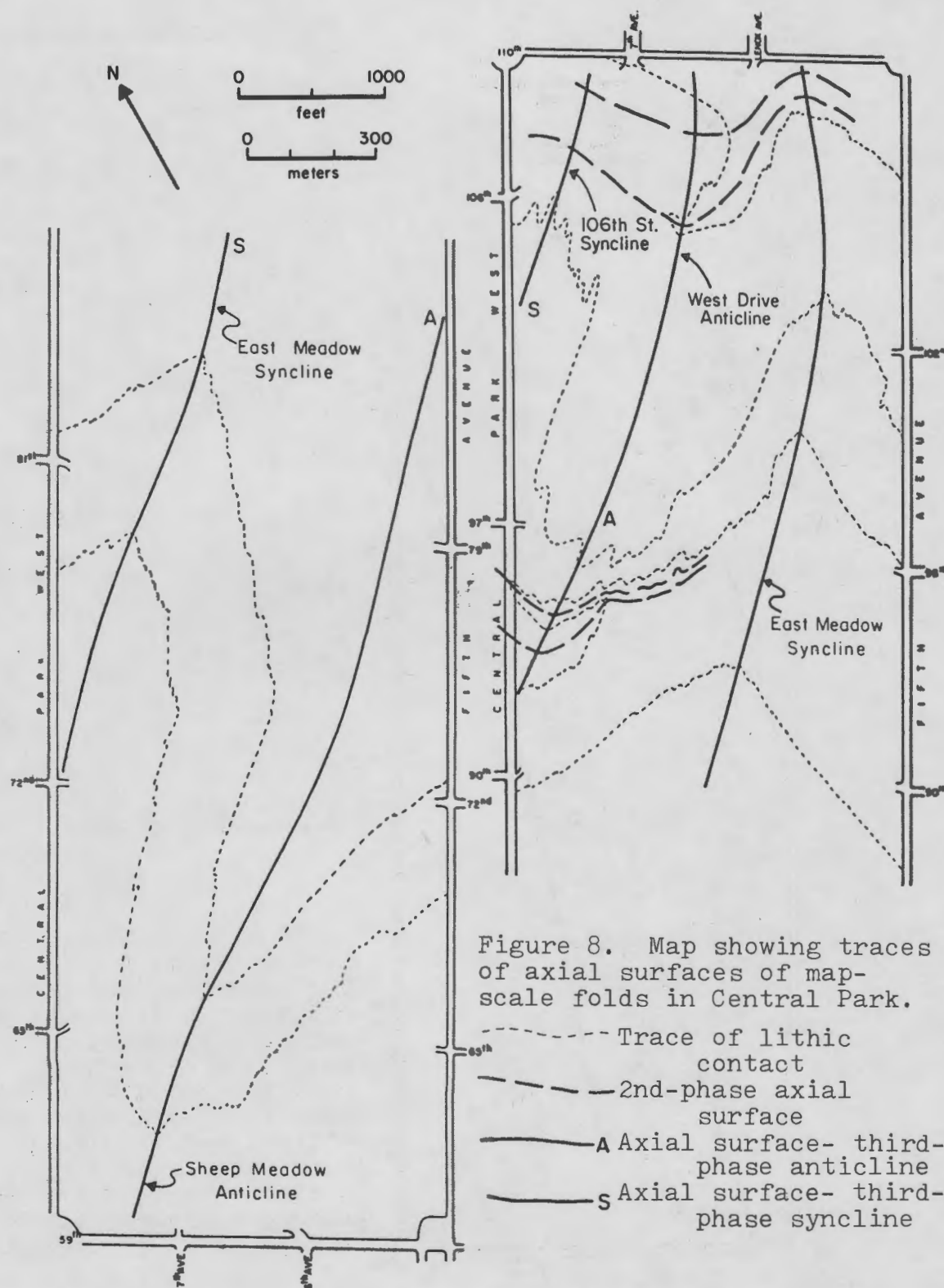
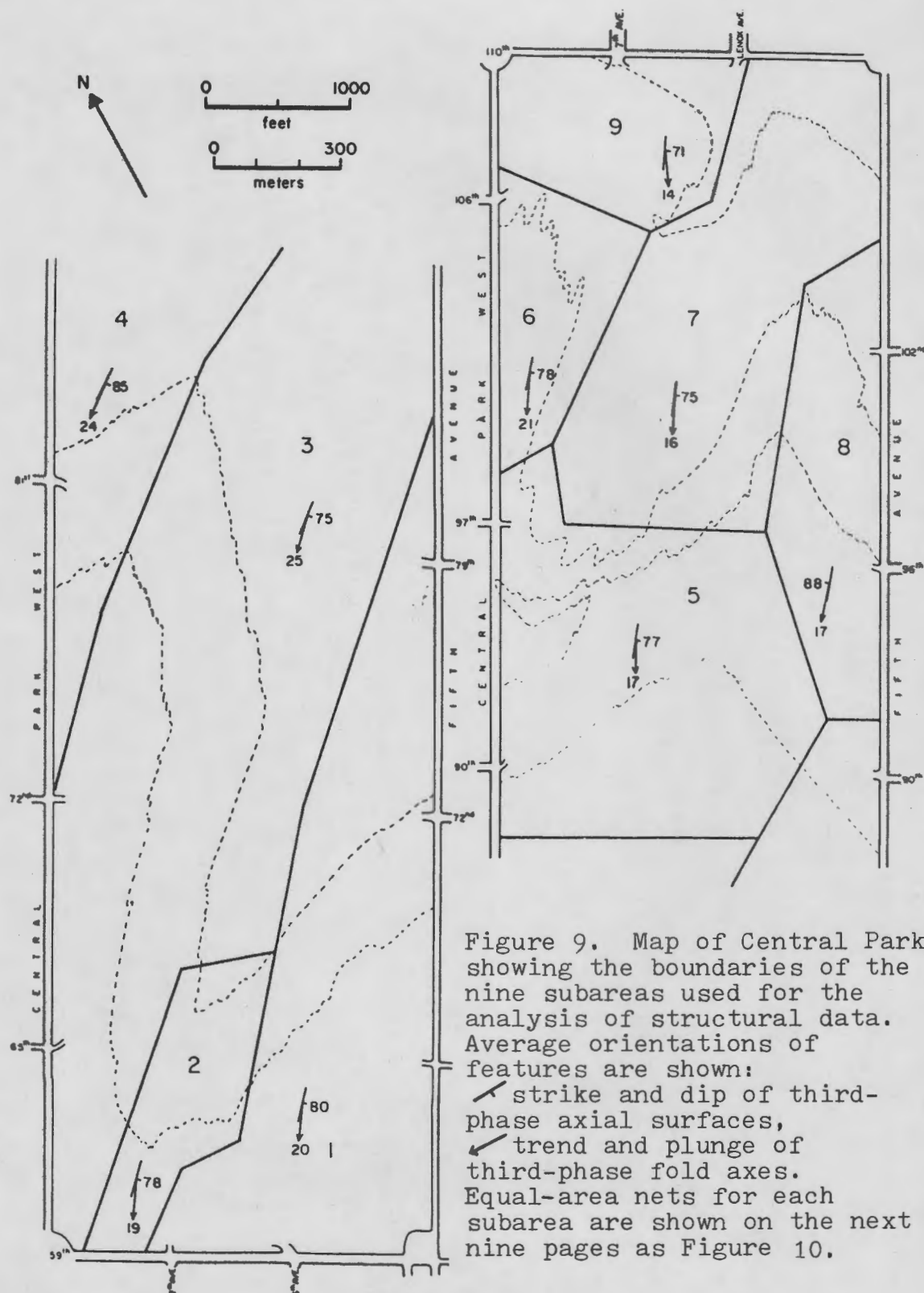


Figure 7. Equal-area diagram of second-phase structural features.





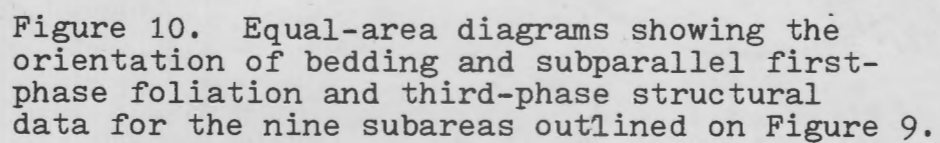
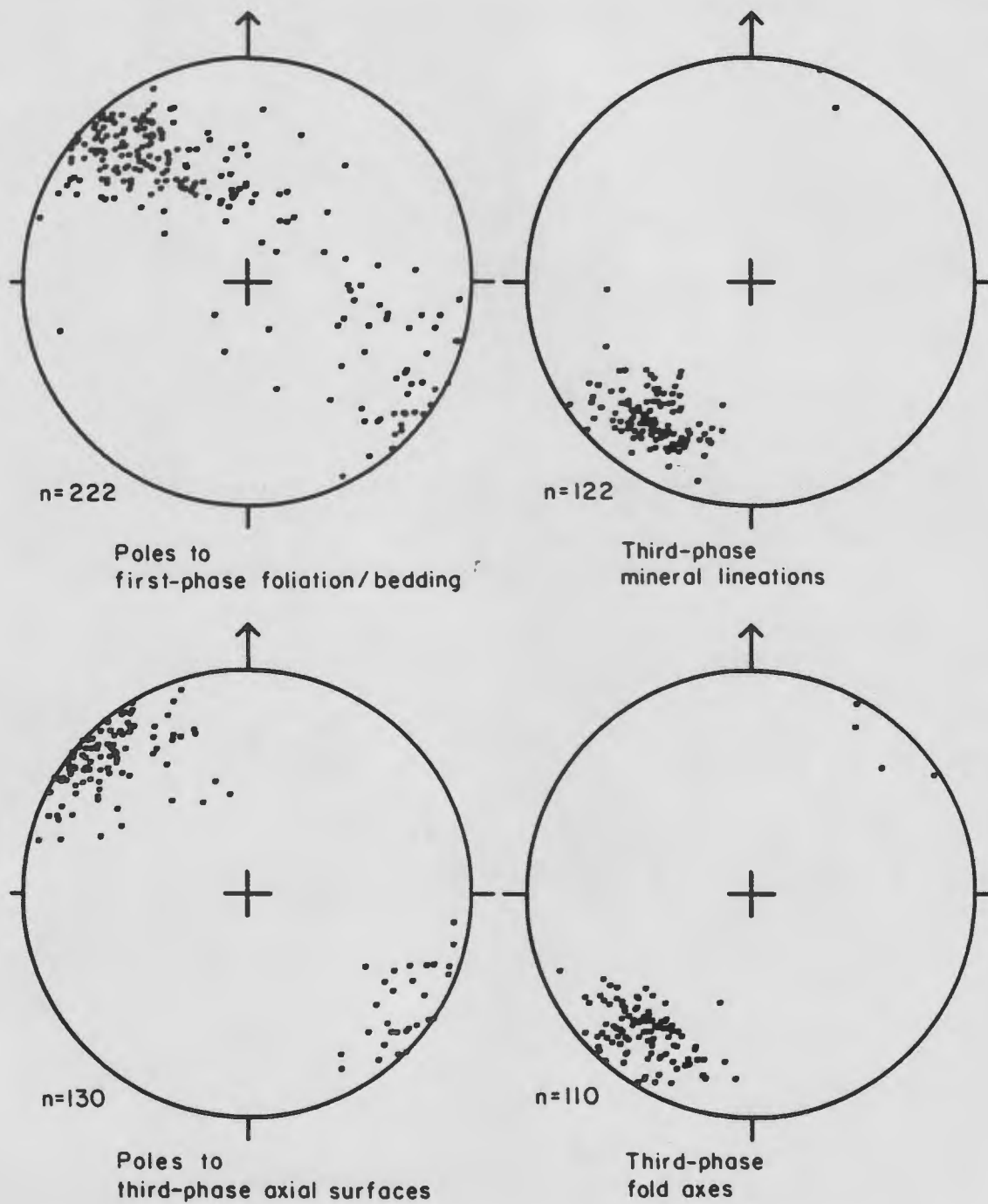
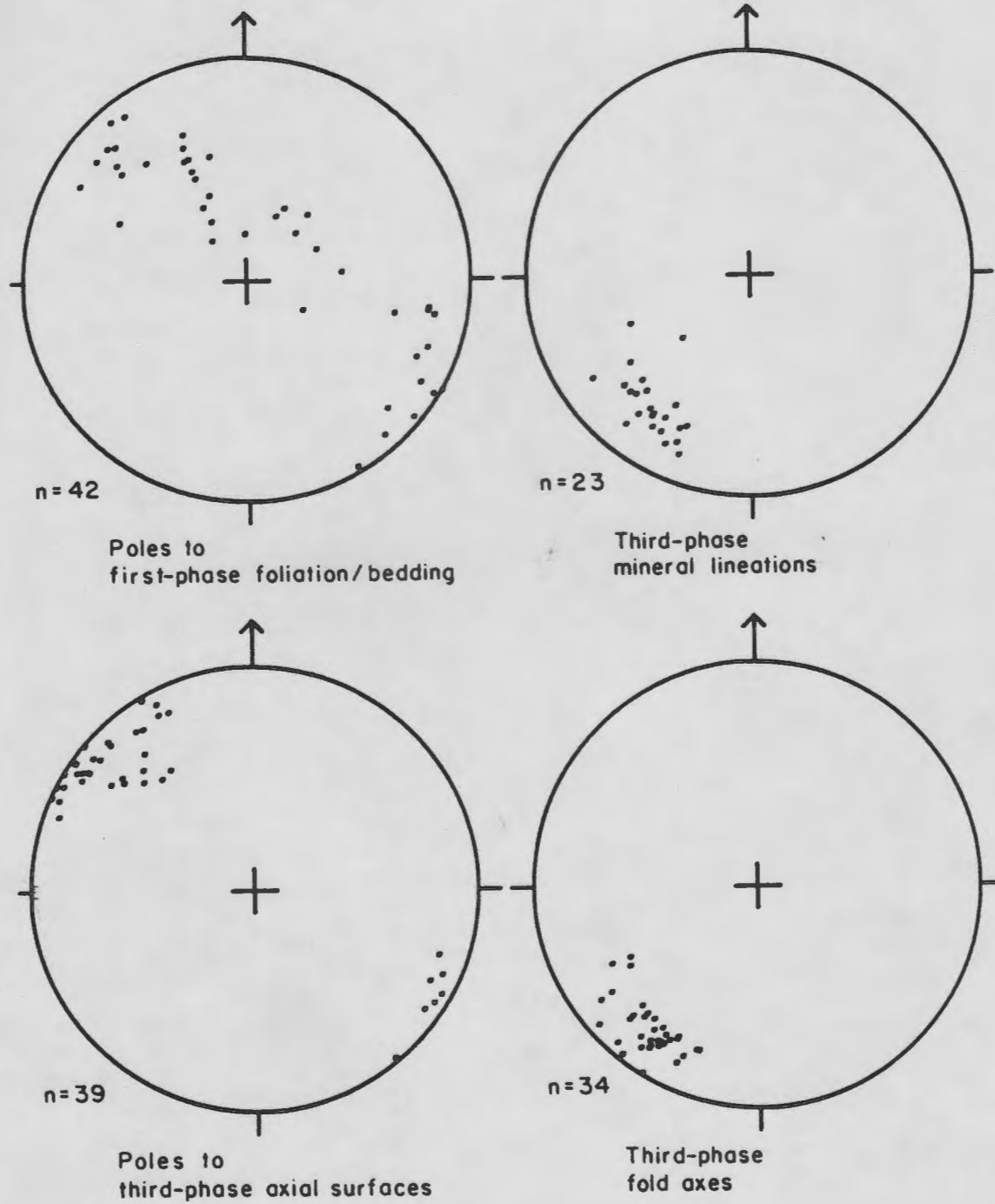


Figure 10. Equal-area diagrams showing the orientation of bedding and subparallel first-phase foliation and third-phase structural data for the nine subareas outlined on Figure 9.

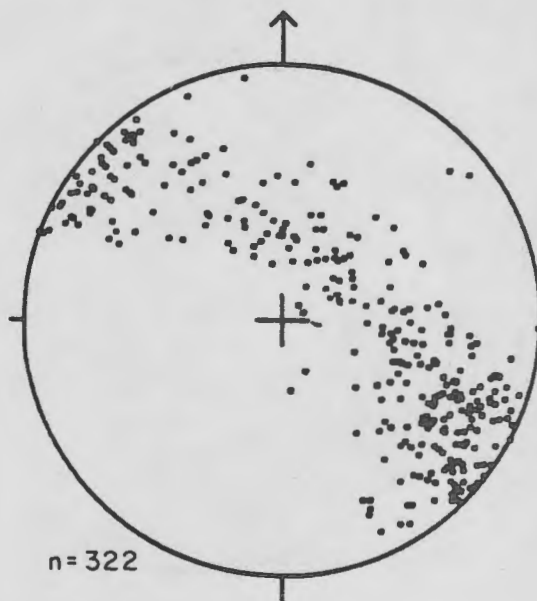
SUBAREA I



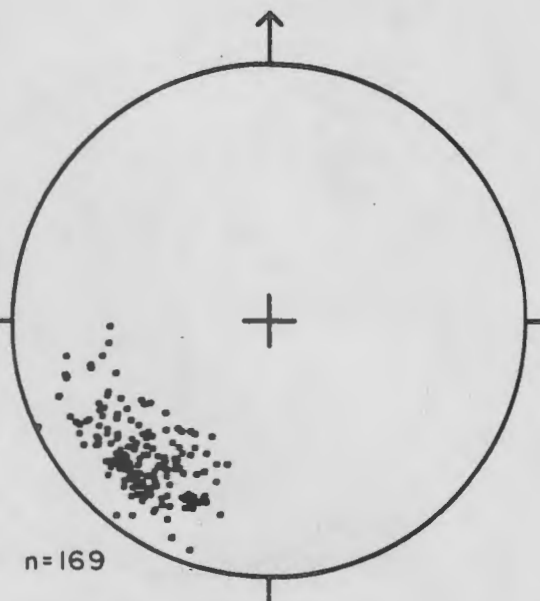
SUBAREA 2



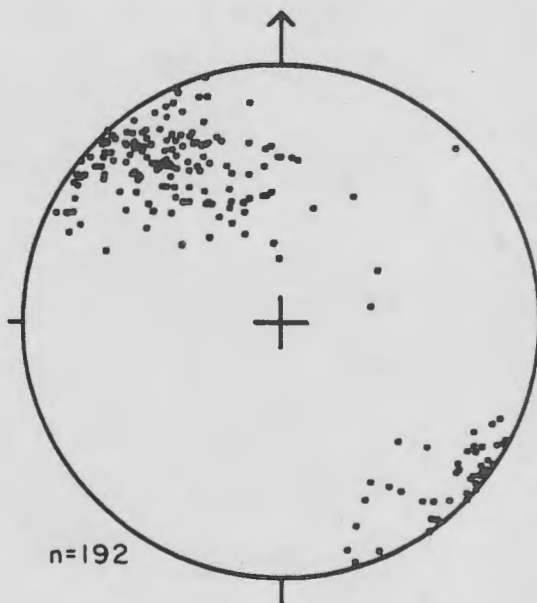
SUBAREA 3



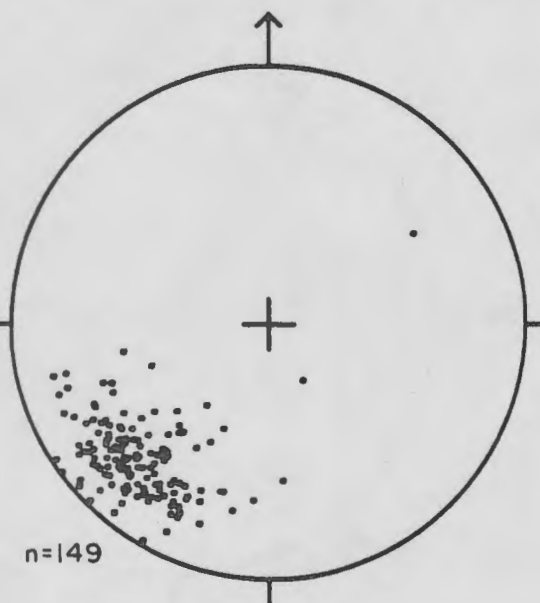
Poles to
first-phase foliation/bedding



Third-phase
mineral lineations

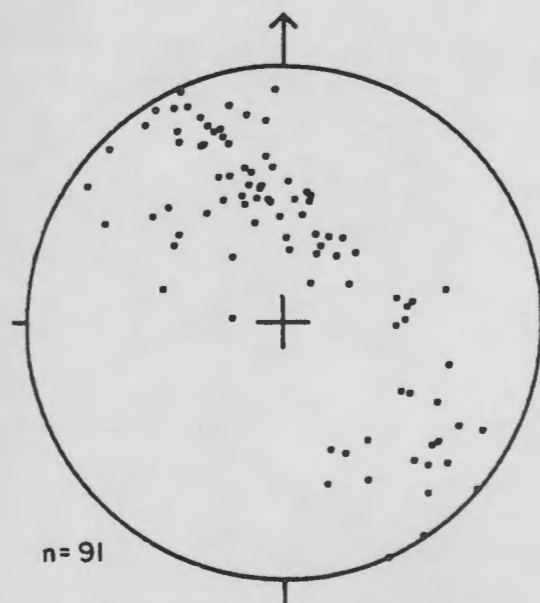


Poles to
third-phase axial surfaces

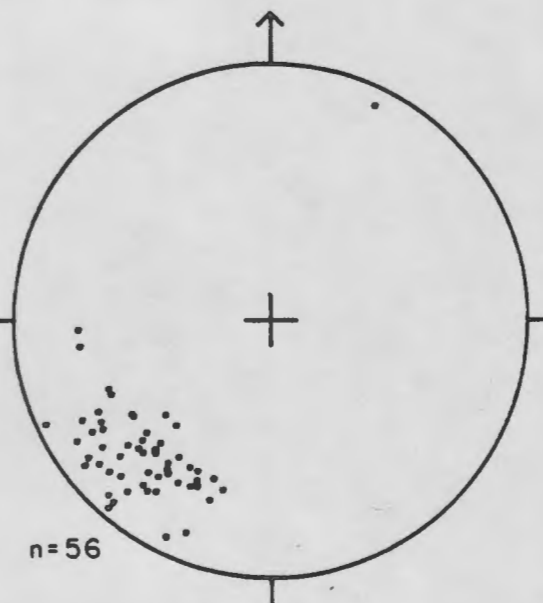


Third-phase
fold axes

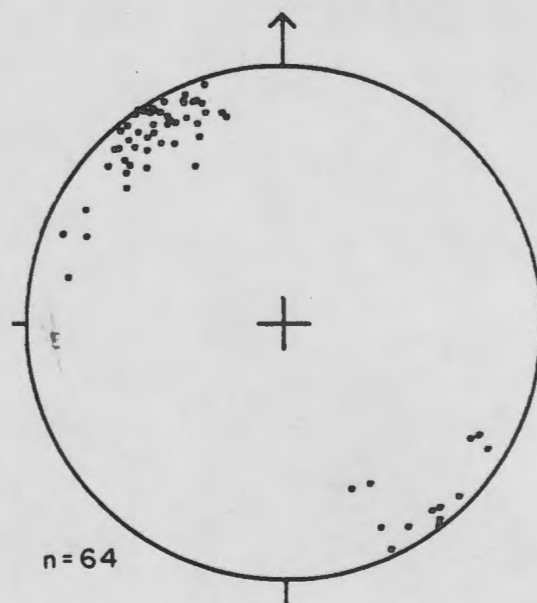
SUBAREA 4



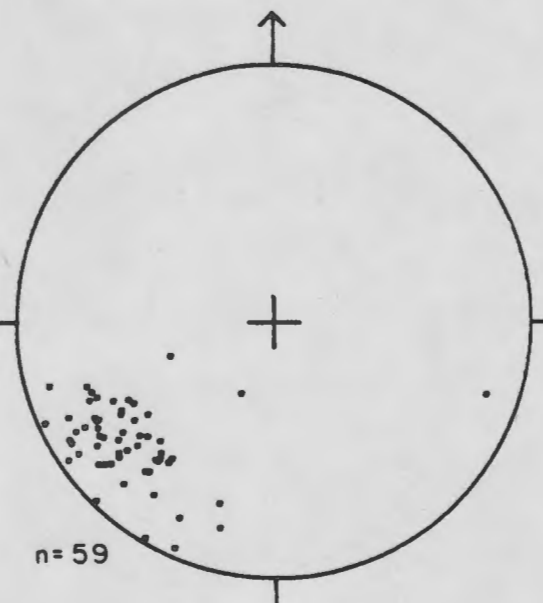
Poles to
first-phase foliation/bedding



Third-phase
mineral lineations

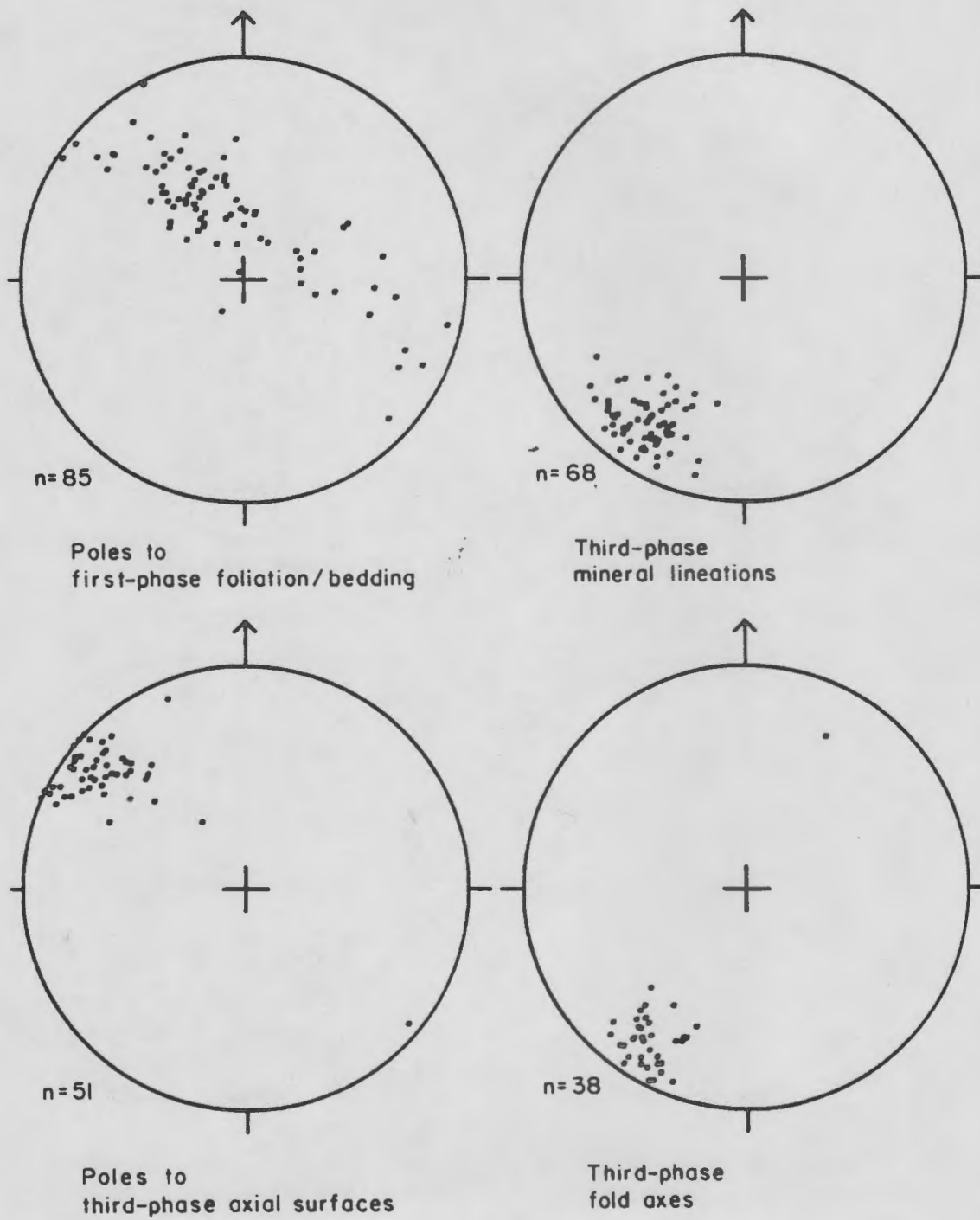


Poles to
third-phase axial surfaces

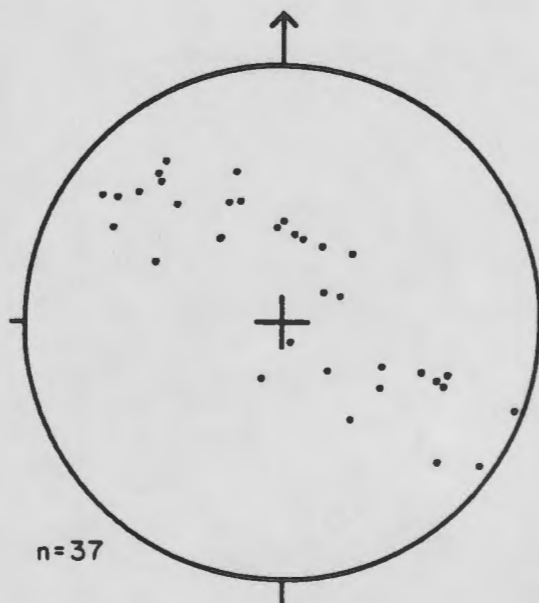


Third-phase
fold axes

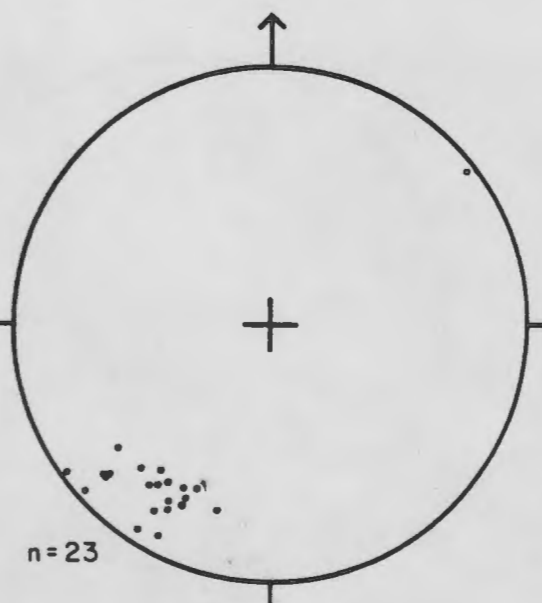
SUBAREA 5



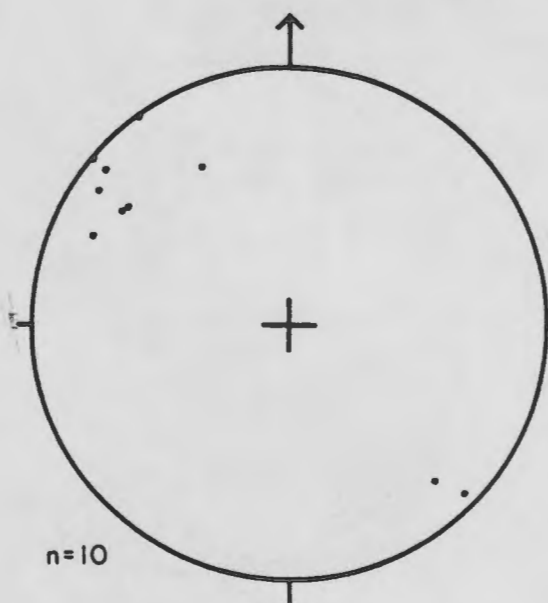
SUBAREA 6



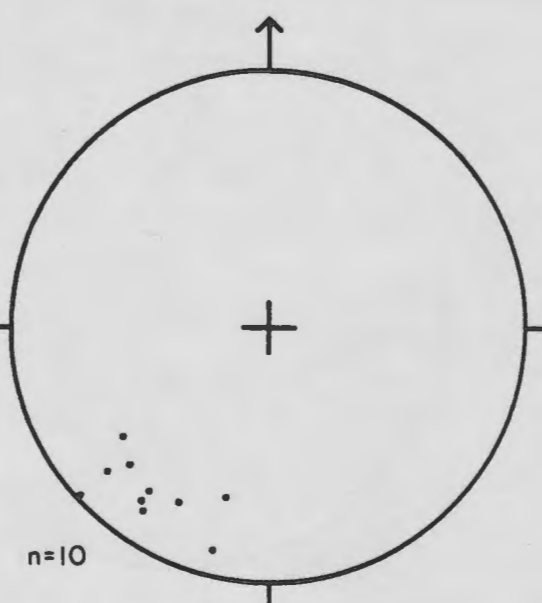
Poles to
first-phase foliation/bedding



Third-phase
mineral lineations

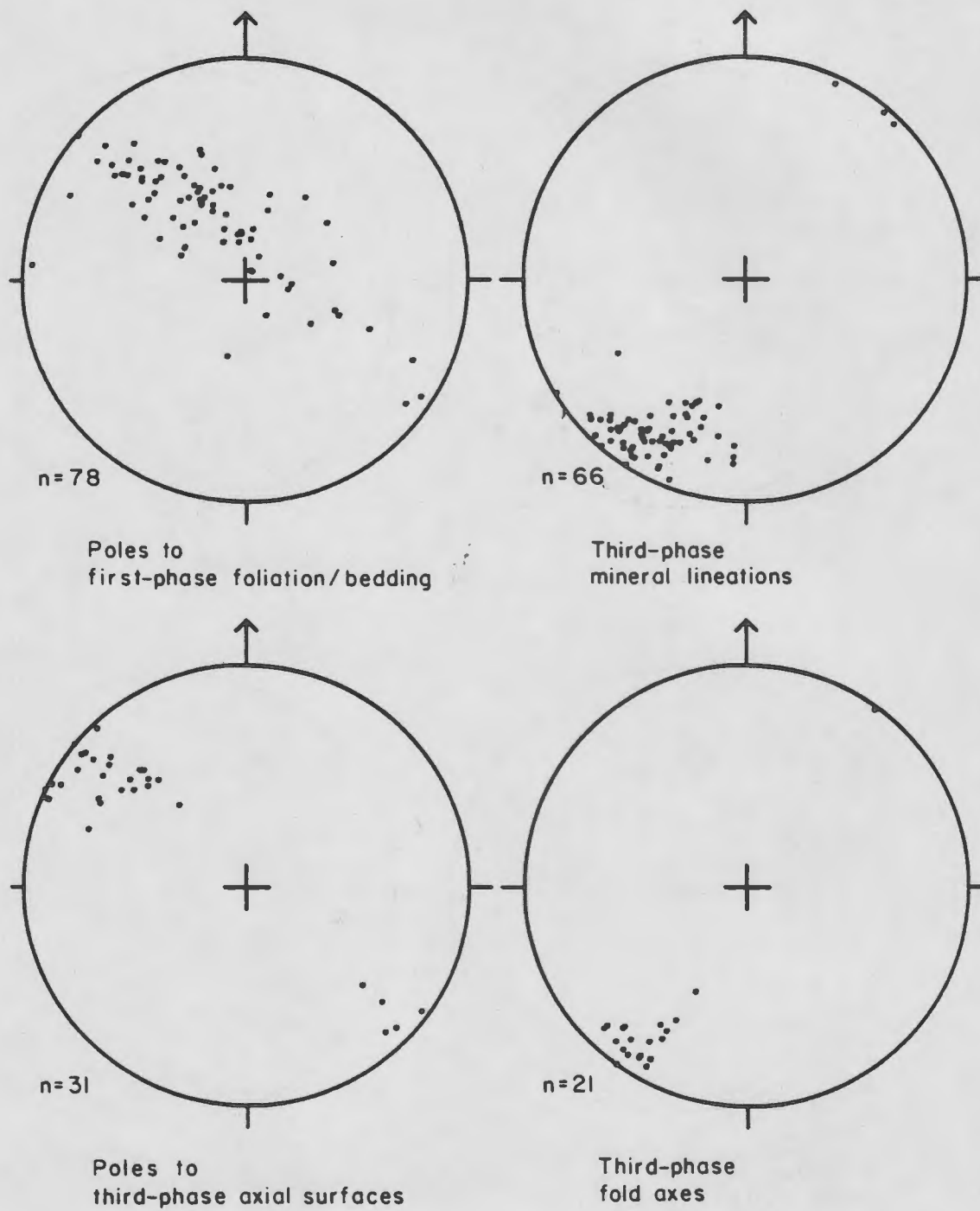


Poles to
third-phase axial surfaces

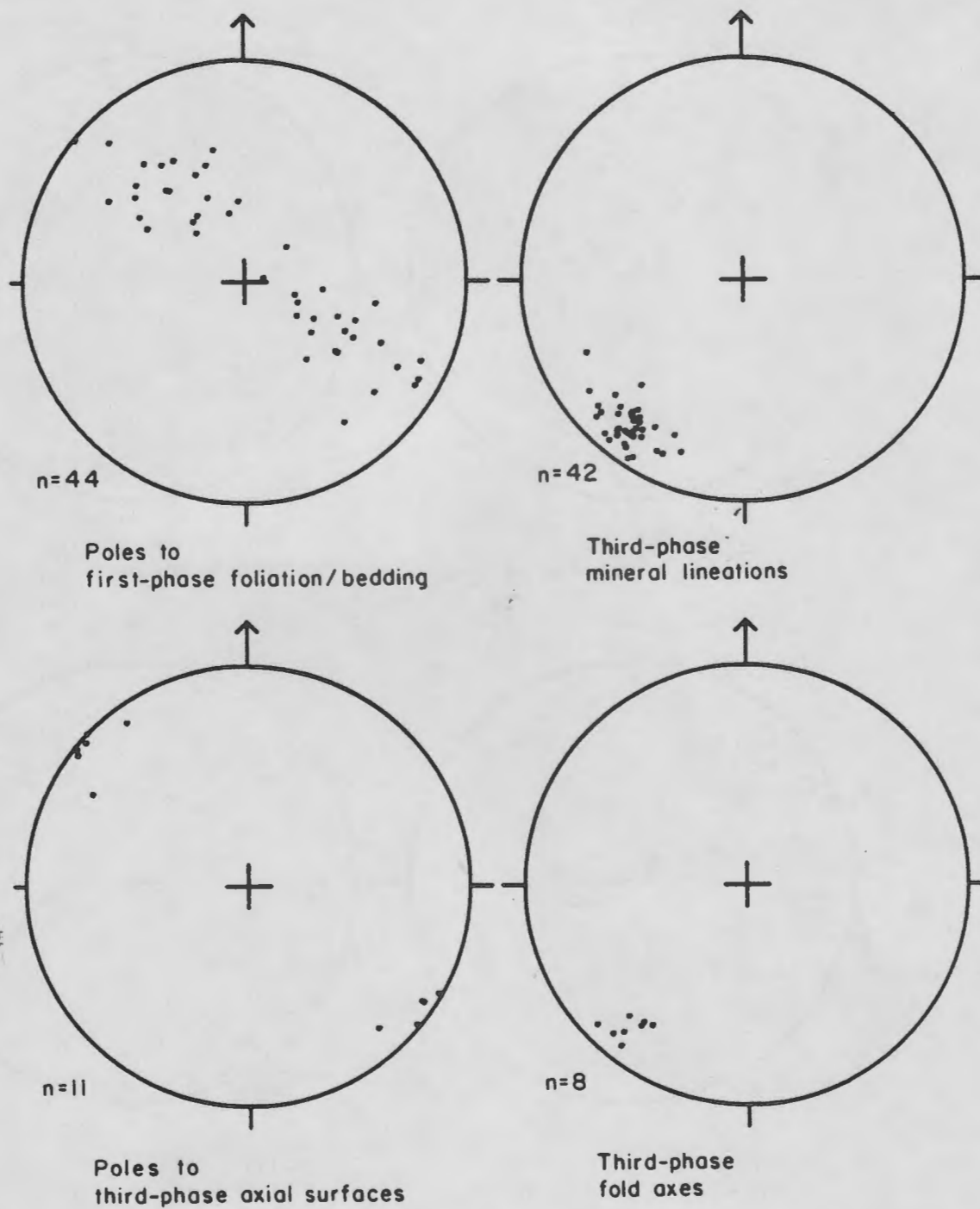


Third-phase
fold axes

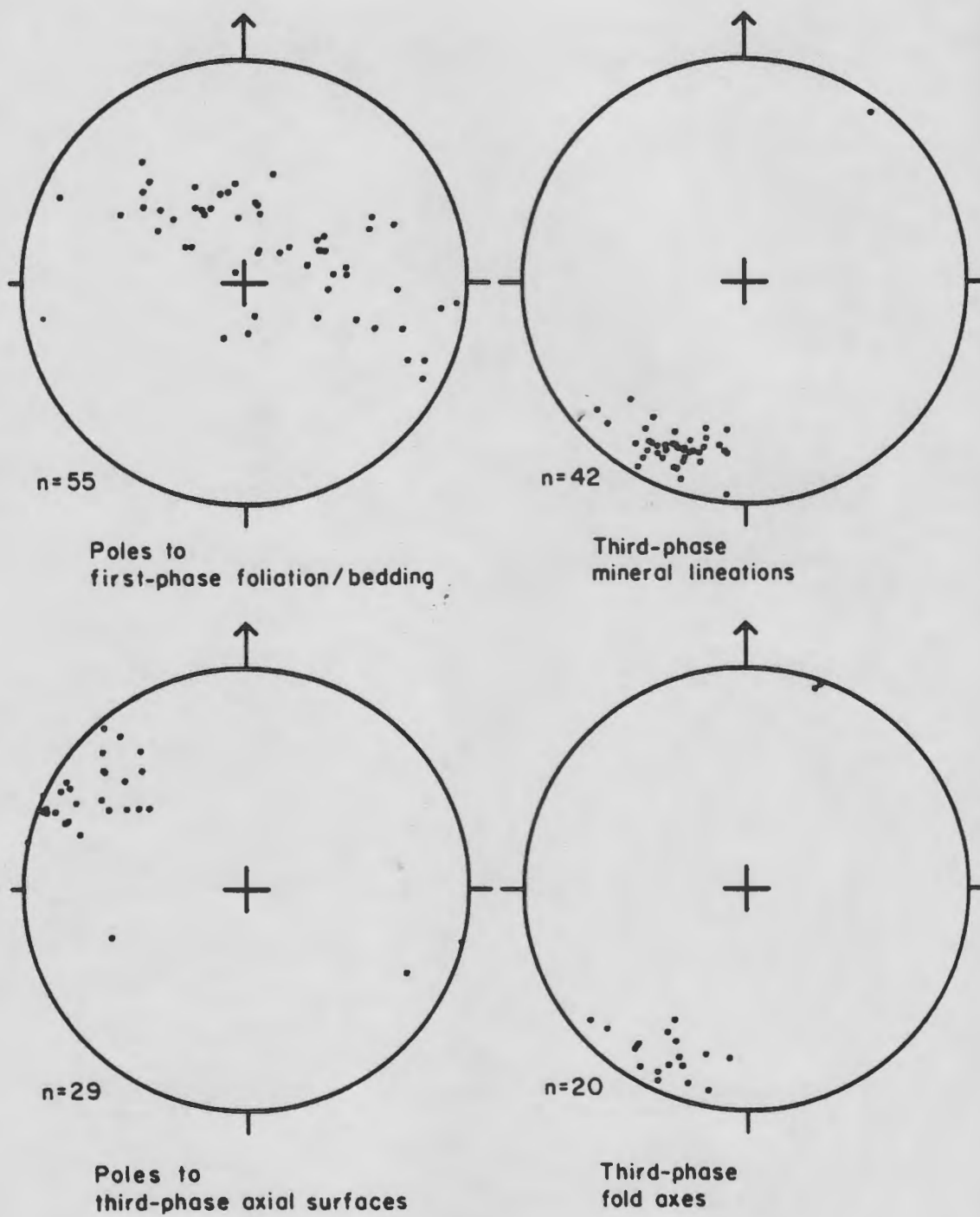
SUBAREA 7



SUBAREA 8



SUBAREA 9



axis orientations in that subarea (Fig. 9, Fig. 10). Geologic features were projected down-plunge or up-plunge through a subarea using the mean fold axis orientation for that subarea. In Plate 2 the cross sections are shown as vertical slices of Central Park geology. The viewer is looking southwest, down the plunge of third-phase fold axes, with the southernmost cross section at the top of the page and the northernmost at the bottom.

FEATURES RELATED TO FIRST-PHASE FOLDING

Foliation

Evidence for the first phase of folding is the dominant foliation subparallel to bedding. This foliation is observed at all outcrops in the Park and is defined by the parallel alignment of micas and by segregation layering of light and dark minerals. Depending on the granular content of the rock, segregation layering may be poorly developed with the foliation best marked by the parallel orientation of micas, or it may be absent. In rocks of the Blockhouse Member of the Manhattan Formation and in some outcrops of the Schist and Granulite Member there are flattened kyanite nodules aligned in the first-phase foliation. Coarse muscovite in the Schist and Granulite Member is also aligned in the first-phase foliation (Fig. 11).

First-phase foliation in amphibolite beds is defined by the segregation of thin, light-colored, plagioclase-quartz layers in the black amphibolite. This foliation can be striking or it can be poorly developed, depending on the amount of light-colored minerals present in the rock.

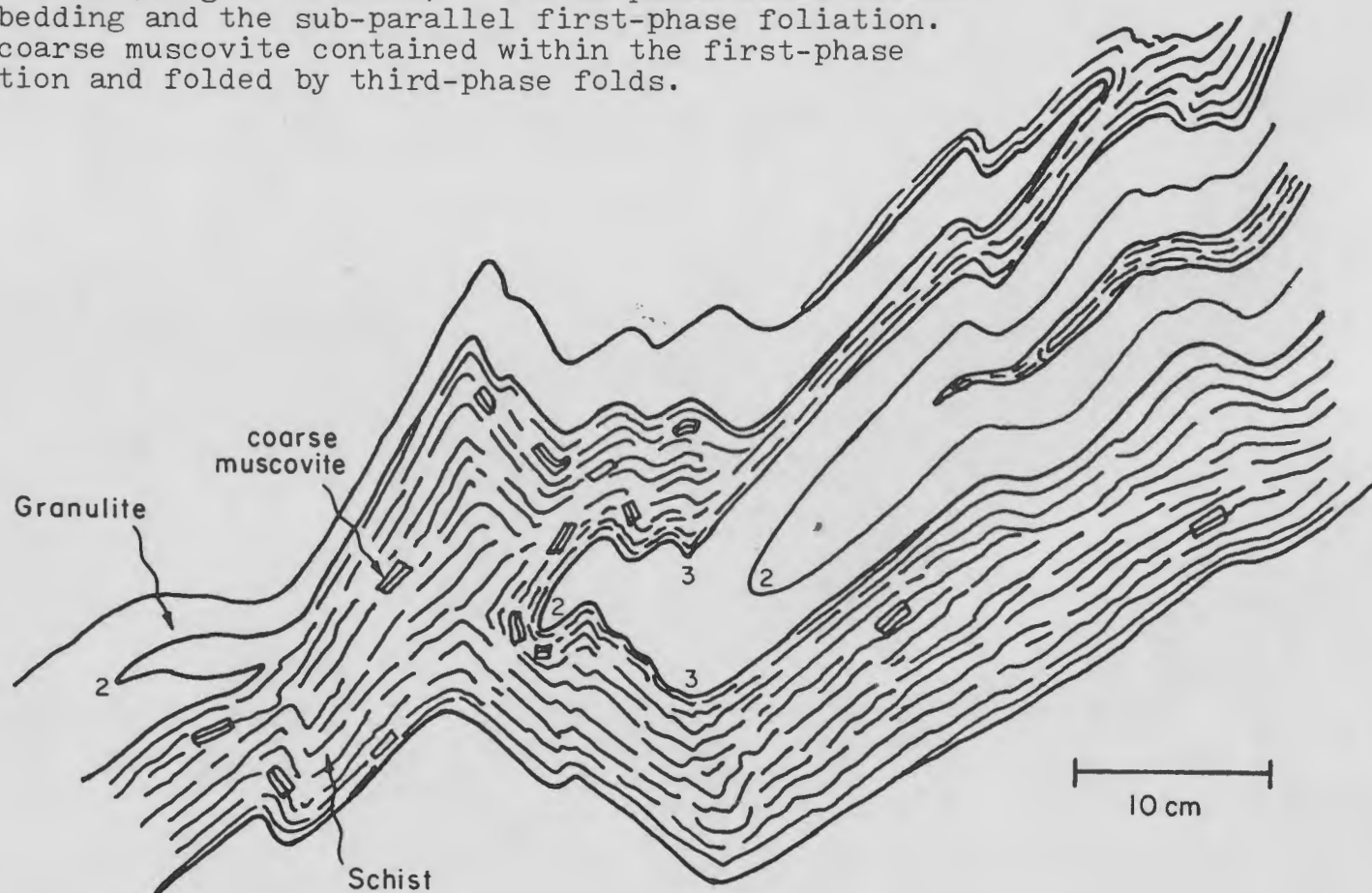
In equal-area projection, poles to first-phase foliation and bedding lie along a great circle whose pole is the third-phase fold axis (Fig. 10).

Folds

Based on the low angle of first-phase foliation to bedding, and the orientation of the few first-phase folds observed in outcrop, the major first-phase folds are believed to have been isoclinal and recumbent with east-west-trending hinge lines.

In outcrop, first-phase folds are recognized as the early fold phase in boomerang-shaped interference patterns. First-phase folds are not definitely recognized in map pattern, although this possibility is discussed later under the section titled "Alternative Structural

Figure 11. Sketch from the large outcrop 25m east of the Heckscher Puppet House. View is S10°W. Hook-shaped interference pattern is the result of second- and third-phase folds (hinges numbered). Second-phase folds deform both bedding and the sub-parallel first-phase foliation. Note coarse muscovite contained within the first-phase foliation and folded by third-phase folds.



Interpretations." To positively identify a first-phase fold in outcrop it is necessary to see the dominant foliation parallel to the axial surface, and to see the axial surface deformed by a later fold phase. It is necessary to see the axial surface deformed because third-phase folds also can have an axial-plane foliation. Langer and Bowes (1969) studied the phases of folding in the rocks of Manhattan Island and called the first phase the "Riverside Fold phase." They described these folds as intrafolial folds with the dominant foliation axial planar to them. Langer and Bowes called the second phase of folding the "Central Park phase," which corresponds to the third phase of folding described in this study. Langer and Bowes described "Central Park phase" folds as tight to isoclinal and noted that they also can have an axial-plane foliation, but they did not use a deformed axial surface as a criterion for recognizing first-phase folds. However, the east-west trend of first-phase hinge lines was observed both by Langer and Bowes and by me.

FEATURES RELATED TO SECOND-PHASE ISOCLINAL RECUMBENT FOLDING

Minor Folds

Second-phase minor folds are tight to isoclinal, deforming bedding and first-phase foliation. They are reclined, recumbent folds with shallowly southwest-dipping axial surfaces (Fig. 6, Fig. 7). Fold axes generally trend southwest and plunge 10° - 25° . Fold amplitude in outcrop is on the order of 5-30cm with wavelength up to 10cm.

Second-phase folds are characteristically seen as the early fold phase in hook patterns produced by the interference of second- and third-phase folds. These structures are best seen in interbedded rocks where bedding and first-phase foliation are folded by second-phase folds, and second-phase axial surfaces are refolded by third-phase folds (Fig. 11). No foliation or lineation associated with second-phase folding was observed. This phase of folding does not fit in with the structural sequence outlined by Langer and Bowes (1969).

Map-Scale Evidence

In the map pattern second-phase folds occur west of the 96th St. tennis courts and on the east side of the Great Hill, west of Lasker Pool (Plate 1). The map-scale second-phase fold hinges are not exposed, but they are inferred based on mapped contacts and the asymmetry of second-phase minor folds, where available. At outcrop W6-9

(Plate 1), which is on the lower limb of a southwest-dipping second-phase recumbent fold, the asymmetry of second-phase folds is anticlockwise, indicating that the map-scale fold closes to the west.

FEATURES RELATED TO THIRD-PHASE UPRIGHT FOLDING

Minor Features

Folds. Third-phase folds are the dominant fold set in the Park, deforming bedding, first-phase foliation, and second-phase axial surfaces. Third-phase axial surfaces strike northeast and mainly dip steeply southeast, although a few vertical to steep northwest dips are recorded (Fig. 10). Fold axes plunge gently southwest, coaxial with second-phase fold axes (compare Fig. 7, Fig. 10). The orientation of third-phase axial surfaces and fold axes is very consistent throughout the Park, as shown by comparing the general structural trends for the nine structural subareas outlined in Figure 9.

The style of third-phase folding is variable depending on lithology and location of the outcrop. They vary from broad folds with amplitude and wavelength on the scale of meters to tight centimeter-sized isoclinal folds. It is common to see isoclinal outcrop-scale third-phase folds which have drawn the first-phase foliation and bedding into parallelism with third-phase axial surfaces. The equal-area plots (Fig. 10) show that poles to third-phase axial surfaces lie at either side of the great circle defined by poles to first-phase foliation. The overall effect of this is that the general strike of foliation and bedding in outcrop appears to be to the northeast, parallel to third-phase axial surfaces. However, third-phase folding is so pervasive that the enveloping surface actually trends northwest, almost at right angles to the commonly observed foliation and bedding orientation. The enveloping surface is defined as the surface tangential to the hinges of a folded layer (Hobbs, Means, and Williams, 1976, p.167).

Based on geometry the mechanism of third-phase folding is predominantly flexural flow (Donath and Parker, 1964). In the interbedded rocks of the Schist and Granulite Member folded layers commonly show some degree of thickening on hinges and thinning on limbs, with more flow within schistose layers than in granular layers.

Foliation. An axial-plane foliation is locally developed in the hinge regions of third-phase folds (Fig. 12). This foliation is defined by 3-10mm muscovite growing parallel to the axial surface, and it is best developed at

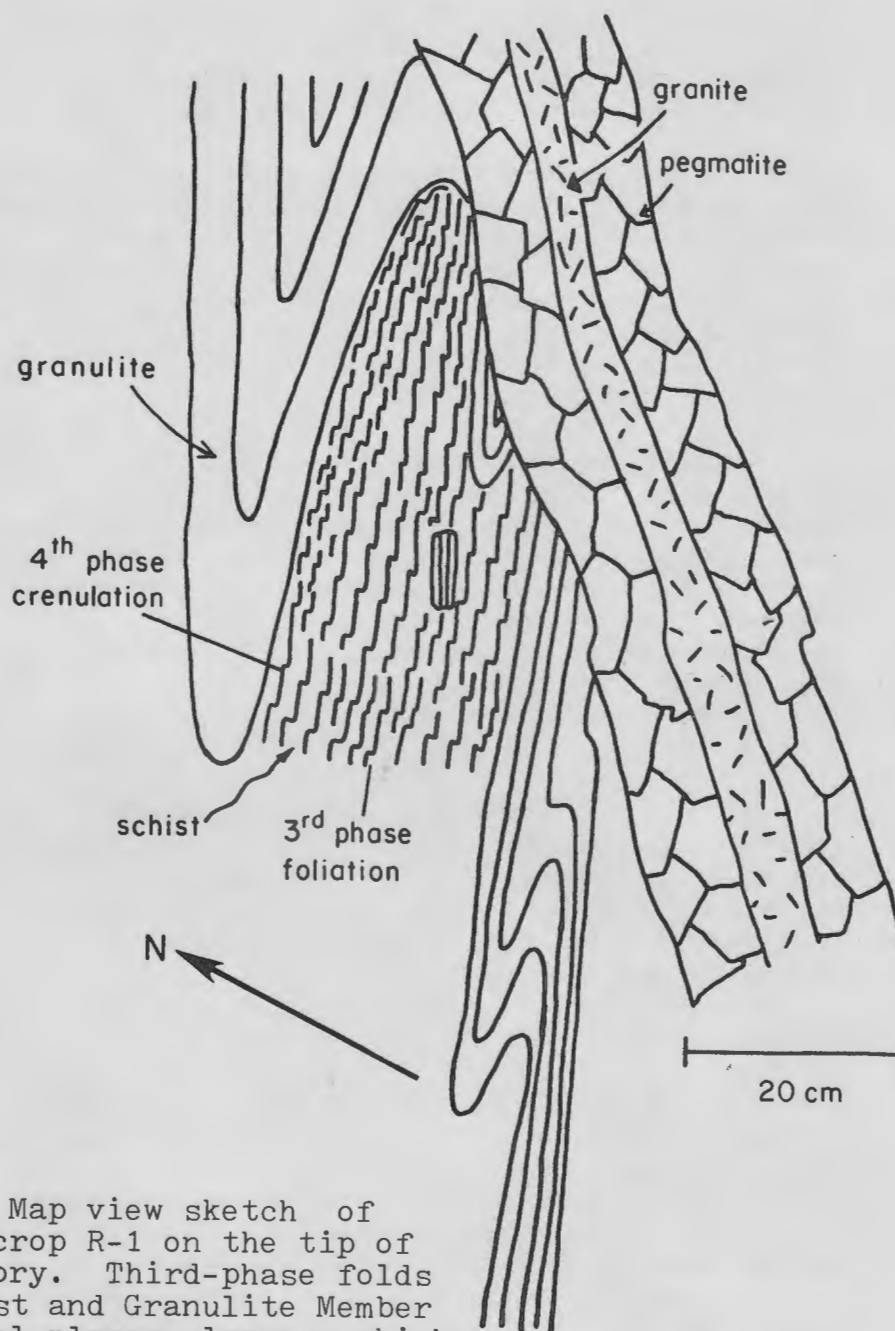


Figure 12. Map view sketch of part of outcrop R-1 on the tip of the Promontory. Third-phase folds in the Schist and Granulite Member have an axial planar cleavage which is deformed by a north-south-trending fourth-phase crenulation cleavage. Note coarse muscovite in third-phase foliation in schist. Third- and fourth-phase structure is cross cut by a late granite-pegmatite 'sandwich.'

fold hinges in tightly folded muscovite-rich schistose beds. On the limbs of a tight fold the third-phase foliation becomes indistinguishable from the first-phase foliation because both are at a low angle to bedding.

Lineation. A mineral lineation associated with third-phase folds is developed on folded bedding and first-phase foliation surfaces. This lineation is parallel to third-phase fold axes (Fig. 10). In schist it is defined by muscovite and biotite while in granulite it is a parallel alignment of quartz and feldspar or fine biotite. In amphibolite it is defined by the parallel alignment of amphibole grains.

Boudinage. Rocks with a ductility contrast are common in the Park, usually as layers of less ductile amphibolite, granulite, granite, pegmatite, or quartz veins in a more ductile schist. The less ductile layers show pinch-and-swell structure and boudinage. Scar folds deform bedding and the first-phase foliation, but the nature of the outcrop usually makes the measurement of these folds impossible. Pinch-and-swell structure may have occurred during second- or third-phase folding, or both, or it may be the result of a separate event.

Where third-phase folding is tight it is common to see quartz veins broken across the short limbs of folds. The broken vein shows an echelon offset indicating the sense of asymmetry of third-phase folding. This can be a useful feature in otherwise homogeneous schist outcrops where the structure may be obscure.

Map-Scale Features

In map pattern, the largest third-phase folds are upright, northeast-striking, southwest-plunging anticlines and synclines (Fig. 8, Plate 1). These folds have amplitude on the order of 500m and wavelength of 900m (Plate 2). The apparent amplitude seen in map pattern is exaggerated due to the shallow plunge.

Outcrop-scale folds developed on the limbs of map-scale folds have a sense of asymmetry consistent with their position in relation to the larger fold. Due to the large size of the first-order third-phase folds there are large areas of the Park where the asymmetry of the third-phase folds seen in outcrop is remarkably consistent (Plate 1). Third-phase folds between the West Drive anticline and the East Meadow syncline are clockwise; those between the East Meadow syncline and the Sheep Meadow anticline are

anticlockwise; and those to the east of the Sheep Meadow anticline are clockwise.

INTERFERENCE PATTERNS

The interference of second- and third-phase folds produces hook-shaped interference patterns (Fig. 11) of type 3 of Ramsay (1962). The geometry of this interference structure is illustrated in Figure 13a. Second-phase axial surfaces are gently southwest-dipping and reclined, while third-phase folds are upright and coaxial with second-phase folds. The movement line for the third phase of folding must lie within the third-phase axial surface, outside of the second-phase fold interlimb angle. Since the limbs of a second-phase fold are essentially parallel, all that can be said of the third-phase movement line is that it lies within the third-phase axial surface at a high angle to second-phase axial surfaces. Thus a vertical line is a reasonable, though not necessarily correct, approximation of the third-phase movement line.

Boomerang-shaped interference patterns of type 2 of Ramsay (1962) are believed to be the result of first- and third-phase interference (Fig. 13b). They are seen at two locations, along Central Park West across from W.103rd St. (Fig. 14) and on the southeast side of the Great Hill, north of The Pool (Plate 1). These interference structures are produced by upright, southwest-plunging third-phase folds refolding recumbent first-phase folds with east-west-trending hinge lines.

Since the axial surfaces of third-phase upright folds are at a high angle to the axial surfaces of first- and second-phase recumbent folds, the resulting interference pattern is dependent on the orientation of the hinge line of the earlier fold phase. Third-phase hinge lines are at a high angle to first-phase hinge lines, so boomerang patterns are produced by their interference. Second- and third-phase folds are coaxial, so hook patterns are the result. The fact that only two boomerang patterns have been observed in the Park while hook patterns are common may be because the effects of second- and third-phase folding have made first-phase folds so tight that they are virtually unrecognizable. The two boomerangs which have been observed are in relatively competent rock types interbedded with schist. One boomerang is granulite and has a fairly tight structure. The other is schist in amphibolite and is extremely tight (Fig. 14). It seems that if a relatively competent amphibolite bed is folded into such a tight structure, a similar feature in a less

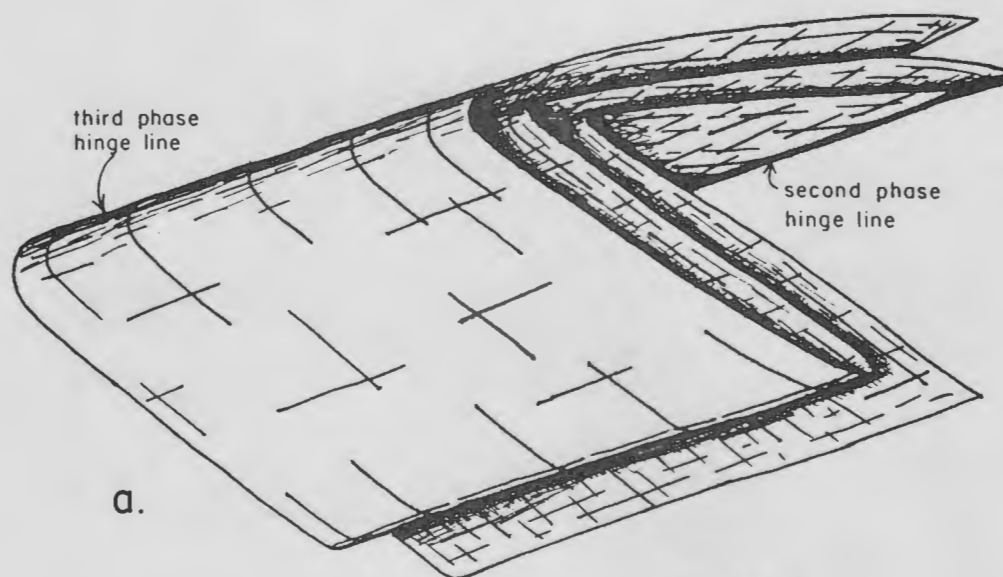
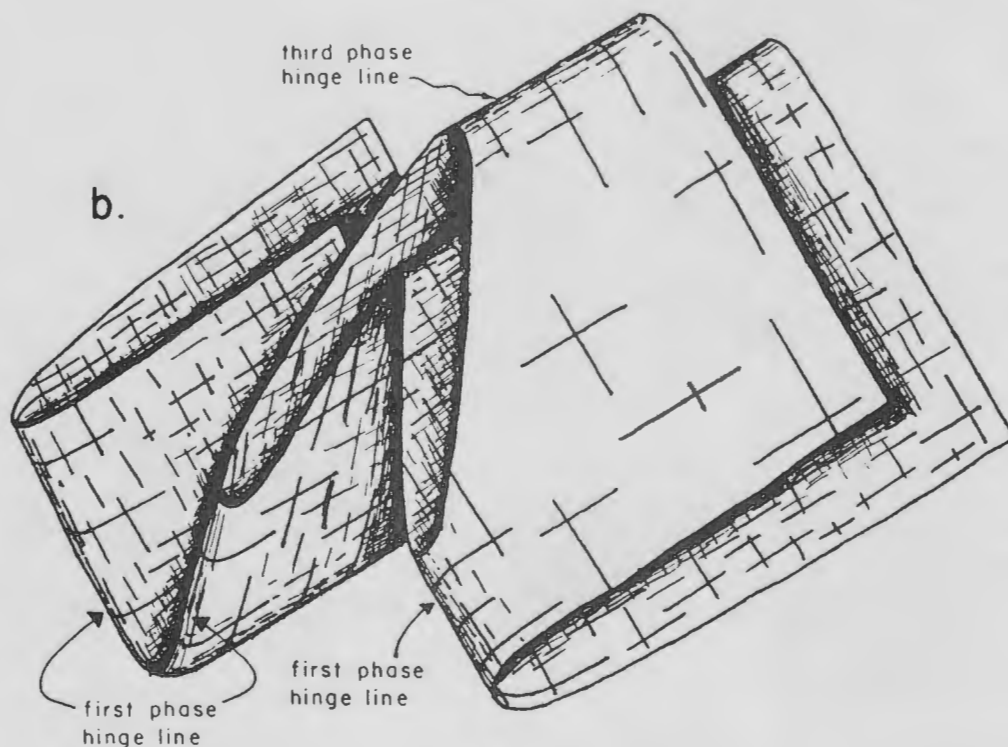


Figure 13. Sketches showing the geometry of interference structures seen in Central Park.

- a) Hook-shaped interference structure produced by second- and third-phase folding.
- b) Boomerang-shaped interference structure produced by first- and third-phase folding.



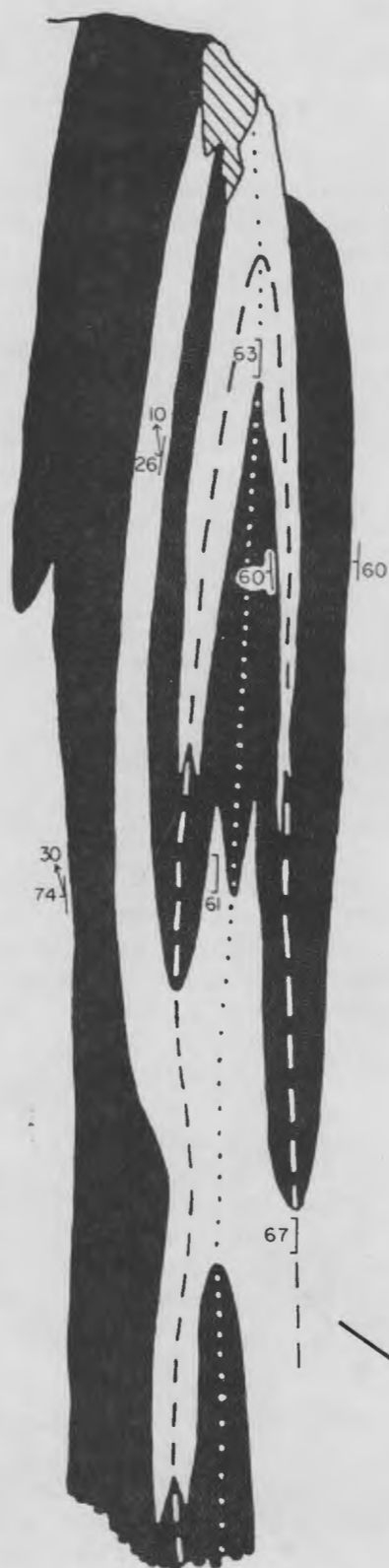


Figure 14. Map view sketch of part of the steep outcrop opposite W.104th St. Amphibolite beds (black) are interbedded with schist of the East Meadow Member (white). The structure shown is a result of first- and third-phase folds, producing a boomerang pattern (see Fig. 13b). The first-phase axial surface, shown dashed, is folded by a third-phase axial surface, shown dotted.

- strike and dip of bedding
- trend and plunge of mineral lineation
- strike and dip of axial surface

Ruled pattern is a quartz vein.

competent rock would be so strongly deformed that it would be impossible to identify.

FEATURES RELATED TO FOURTH-PHASE FOLDING

Minor Folds

Fourth-phase folds are best developed at the south end of the Park, at the outcrops immediately north of the corner of 6th Ave. and 59th St. (Plate 1). The axial surfaces of these folds strike roughly north-south and dip steeply west (Fig. 15). They are fairly open, with amplitude and wavelength on the order of 10-100cm. At outcrop E12A-9 (Plate 1) fourth-phase folds deform both a thin quartz vein and the axial surface of a third-phase fold in a granulite bed, giving it the appearance of a large, bent tongue. At outcrop E12A-8 (Plate 1), 5m west of the rustic shelter, fourth-phase folds deform third-phase axial surfaces.

Cleavage

A crenulation cleavage developed in first- and third-phase foliation is axial planar to fourth-phase folds (Fig. 15). This cleavage is well displayed at outcrop E12A-9 (Plate 1) where it is a pervasive, closely spaced, centimeter-sized folding of segregation layers and individual mica grains in the first-phase foliation.

Figure 12 is a sketch of part of outcrop R-1 (Plate 1) on the east side of the south tip of the Promontory. This illustrates the fourth-phase crenulation cleavage deforming a third-phase axial-plane foliation, proving that the cleavage is younger than third-phase folds.

FIFTH-PHASE FOLDING

Fifth-phase folds are open, upright folds with amplitude and wavelength on the scale of meters. They are visible in outcrop as broad warps in bedding, foliation, and third-phase axial surfaces. The large size and openness of these folds makes it very difficult to measure their orientation. In map pattern fifth-phase folds are seen as east-west-trending gentle warps in third-phase axial surfaces.

The age relationship between fourth- and fifth-phase features is not firmly established because they are not seen interfering with each other. I believe that they are distinct deformational phases because of their difference in orientation, which is about 90°, and their difference in

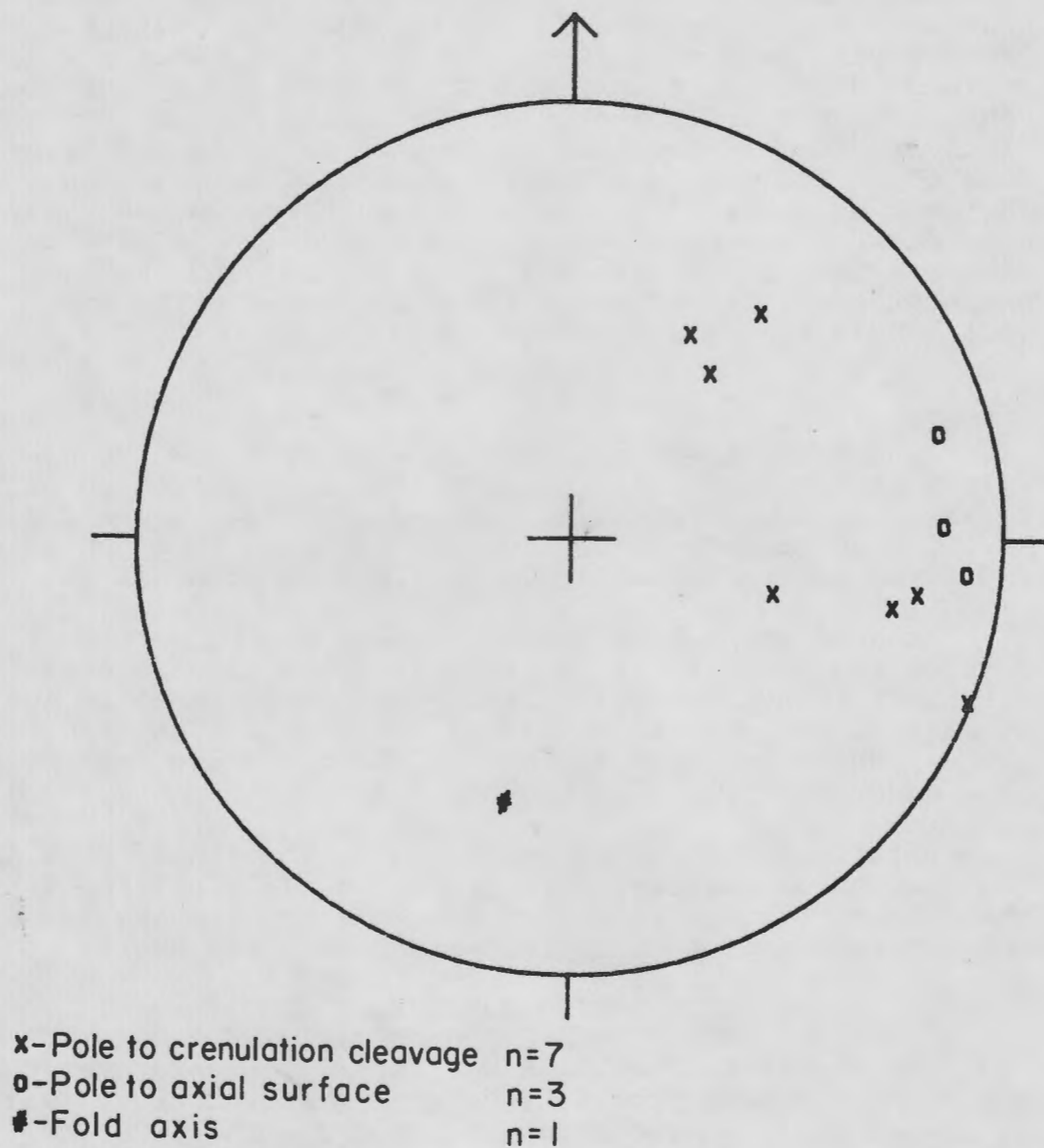


Figure 15. Equal-area diagram of fourth-phase structural features.

style, fourth-phase folds being tighter and generally smaller.

N40W KINKS

Thin, straight kink zones deform first-phase foliation at outcrop E4A-10 (Plate 1) on the east side of the North Meadow, and outcrop W9-6 (Plate 1) about 60m east of Central Park West at W.79th St. These kink zones are up to 3m long, nearly vertical, and strike N40W. They must be younger than third-phase folds since they do not show any of their effects, but they can not be chronologically related to the fourth and fifth phases of deformation. They may be a result of one of these phases, or they may be a product of a separate event. The style of deformation is distinct from the fourth and fifth phases, and the orientation of the kinks is 45° from both fourth- and fifth-phase features.

BRITTLE FAULTS

At outcrop E3B-2 on the east side of the North Meadow (Plate 1) strike-slip vertical faults displace third-phase folds in interbedded schist and amphibolite. These faults have 1-10cm of left-lateral displacement on them, splaying and dying out to the west over a distance of about 5m.

At outcrop R-55 on the east shore of the northwest cove of the Lake (Plate 1) there are also left-lateral northwest-trending vertical faults cutting granulite and pegmatite. Slickensided vein quartz encrusts the fault planes, which are spaced about 1m apart. These faults are also described by Hanley and Graff (1976).

Brittle faults are inferred to be the final phase in the structural history of the Park, possibly related to the Mesozoic rifting which was responsible for the opening of the Newark Basin and the present day Atlantic ocean.

AGE OF STRUCTURAL FEATURES

The Manhattan Formation was thrust westward over the autochthonous cover rocks along the Elmsford thrust (Hall, in press) early in the Taconian orogeny. The Elmsford thrust is equivalent to the St. Nicholas thrust of Merquerian (1986) and to the faults at the base of the Taconic allochthons in eastern New York and western Vermont (Zen, 1961; Stanley and Ratcliffe, 1985). The rocks of the Hartland Formation originated east of the Manhattan Formation and have been thrust westward along Cameron's Line to their present position above the autochthonous and

allochthonous rocks. The eastern roots of the Elmsford thrust are truncated by Cameron's Line (Spinek and Hall, 1985), indicating that movement along Cameron's Line postdates the Elmsford thrust. Since the thrust faults are probably not exposed in Central Park, no direct evidence of their timing relative to the other phases of deformation was found. On the basis of surface and subsurface mapping in New York City, Merguerian (1983; 1986) has shown that thrusting along Cameron's Line was synchronous with two early progressive phases of Taconian folding. However, in southeastern New York and western Connecticut Hall (1968a) and Spinek and Hall (1985) have demonstrated that thrusting along the Elmsford thrust and along Cameron's Line predates Taconian folding.

Although no radiometric dating has been done in the Park, a number of studies in the Manhattan Prong have used the relationships of dated igneous rocks to structural features for the purpose of putting time constraints on various phases of deformation and metamorphism (Ratcliffe, 1968a; Mose and others, 1976; Brock and Mose, 1979; Brock and Brock, 1985). A review of the literature indicates that the first and second phases of deformation described here are of probable Taconian age. Third-phase folds are recognized on a regional scale and can be traced throughout the Manhattan Prong on the Geologic Map of New York (Fisher and others, 1970), where they maintain a fairly consistent style and orientation. Igneous rocks which are either older or younger than third-phase folds have been radiometrically dated, establishing constraints on the absolute ages of these folds. However, some doubt still remains as to their age.

The Cortlandt Complex, a large igneous intrusion south of the Hudson Highlands, has been studied by Ratcliffe (1968a) and Ratcliffe and others (1982; 1983). Ratcliffe (1968a, p.779) observed that "The prominent local structure is a late northeast-plunging F_2 synform that folds the F_1 axial planes about a $N.60^{\circ}E$ axis and plunges 20° to $25^{\circ}NE$." These folds are cut by igneous rocks of the Cortlandt Complex dated at 435 m.y. (Long and Kulp, 1962). These studies concluded that these prominent folds are coincident with or older than 435 m.y. If the third-phase folds in Central Park are the same as Ratcliffe's (1968a) F_2 folds, which I believe they are, then a Taconian age for third-phase folding is strongly suggested.

Brock and Brock (1985) provide a detailed sequence of deformational and metamorphic events for the northern part of the Manhattan Prong. In the Croton Falls area, F_3 folds are northeast-trending and upright, and described as

"ubiquitous" (p. 255). F₃ folds in the Manhattan Formation are cross-cut by F₄ quartz-feldspar-garnet-sillimanite segregations. An Rb-Sr whole-rock isochron of at least 442 m.y. has been obtained from these segregations (Brock and others, 1985), establishing a Taconian age for F₃ folding.

However, comparisons of third-phase folding in Central Park with the results of other studies suggest that the third phase may be post-Taconian. Mose and others (1976, p.365) observed that an intrusive igneous body adjacent to the Cortlandt Complex, the Peekskill granite, "was syntectonic with a late stage event that folded . . . Manhattan Schist along N40E- to N50E-trending steep folds." The same study dates the Peekskill granite at 371±14 m.y., which implies an Acadian age for these folds, contrary to Ratcliffe (1968a) and Ratcliffe and others (1982; 1983).

It is also possible to trace third-phase folds northward from New York City into areas along Cameron's Line in southeastern New York and western Connecticut. In the White Plains area (Hall, in press) third-phase folds are upright, northeast-striking, and plunge gently northeast. Farther north, in the Bethel quadrangle of western Connecticut (Spinek and Hall, 1985) third-phase folds are reclined, with northeast-trending, northwest-dipping axial surfaces. These folds can be traced northeast into the Newtown quadrangle (Stanley and Caldwell, 1976) where they are described as north-striking F₂ folds with west-dipping axial surfaces. The F₂ folds in Newtown can be traced east into the adjacent Southbury quadrangle (Scott, 1974) where they are described as Period-3 north-northeast-trending upright folds. These folds deform the Silurian-Devonian Straits Schist, establishing a definite post-Taconian age for Period-3. If this correlation between third-phase folds in Central Park and Period-3 folds in the Southbury quadrangle is correct, which seems likely, then third-phase folds must be post-Taconian in age, and are most likely Acadian.

Although the age of third-phase folds is not definitely established, it seems likely that first- and second-phase folding is Taconian. Fourth- and fifth-phase folding are probably Acadian or younger. Their effects are relatively minor, and they are similar in style and orientation to F₄ and F₅ described by Ratcliffe and others (1982; 1983). These phases of deformation affect the 435 m.y. Cortlandt intrusives, suggesting a post-Taconian age. The presence of Acadian deformation in this area is likely, considering that Silurian-Devonian sedimentary rocks west of the Manhattan Prong are folded (Jaffe and Jaffe, 1973).

ALTERNATIVE STRUCTURAL INTERPRETATIONS

The simplest stratigraphic and structural interpretation of Central Park geology is that the East Meadow Member is a layer within the Blockhouse Member, and that the previously described tectonostratigraphic sequence has been deformed as described above. In this interpretation Central Park lies in an upward-facing part of the large-scale regional structure as shown in Figure 16a. However, some poorly understood structural and stratigraphic features suggest the alternative explanations which are put forth here.

1) 110th St. Member is part of the autochthon. The 110th St. Member of the Manhattan Formation is lithically similar to the autochthonous Middle Ordovician Walloomsac Schist described by Hall in the White Plains area (in press). If the 110th St. Member correlates with the Walloomsac Schist, then the lower contact of the Blockhouse Member is actually the Elmsford thrust (Hall, in press) and the contact relations in the Park are as shown in Figure 16b. In this interpretation, the Elmsford thrust is exposed at the north end of the Park and is folded by second- and third-phase folds (Plate 1).

2) Repetition of the Blockhouse Member by first-phase folding. Figure 16c shows an alternative interpretation involving large-scale, isoclinal, first-phase folding. In this scenario the East Meadow Member overlies the Blockhouse Member, and the bottom-to-top stratigraphy within the Manhattan Formation is 110th St. Member - Blockhouse Member - East Meadow Member. First-phase axial surfaces lie within the East Meadow Member and the Blockhouse Member (Fig. 16c), and they cause the repetition of these two units. This is consistent with the map pattern (Plate 1), as the Blockhouse Member is repeated and the East Meadow Member could crop out again south of the Blockhouse Member, in the "area of poor exposure" (Fig. 16c) around the Reservoir. If structures indicating facing direction could be discovered in the Manhattan Formation, this interpretation could possibly be confirmed or denied.

SW

NE

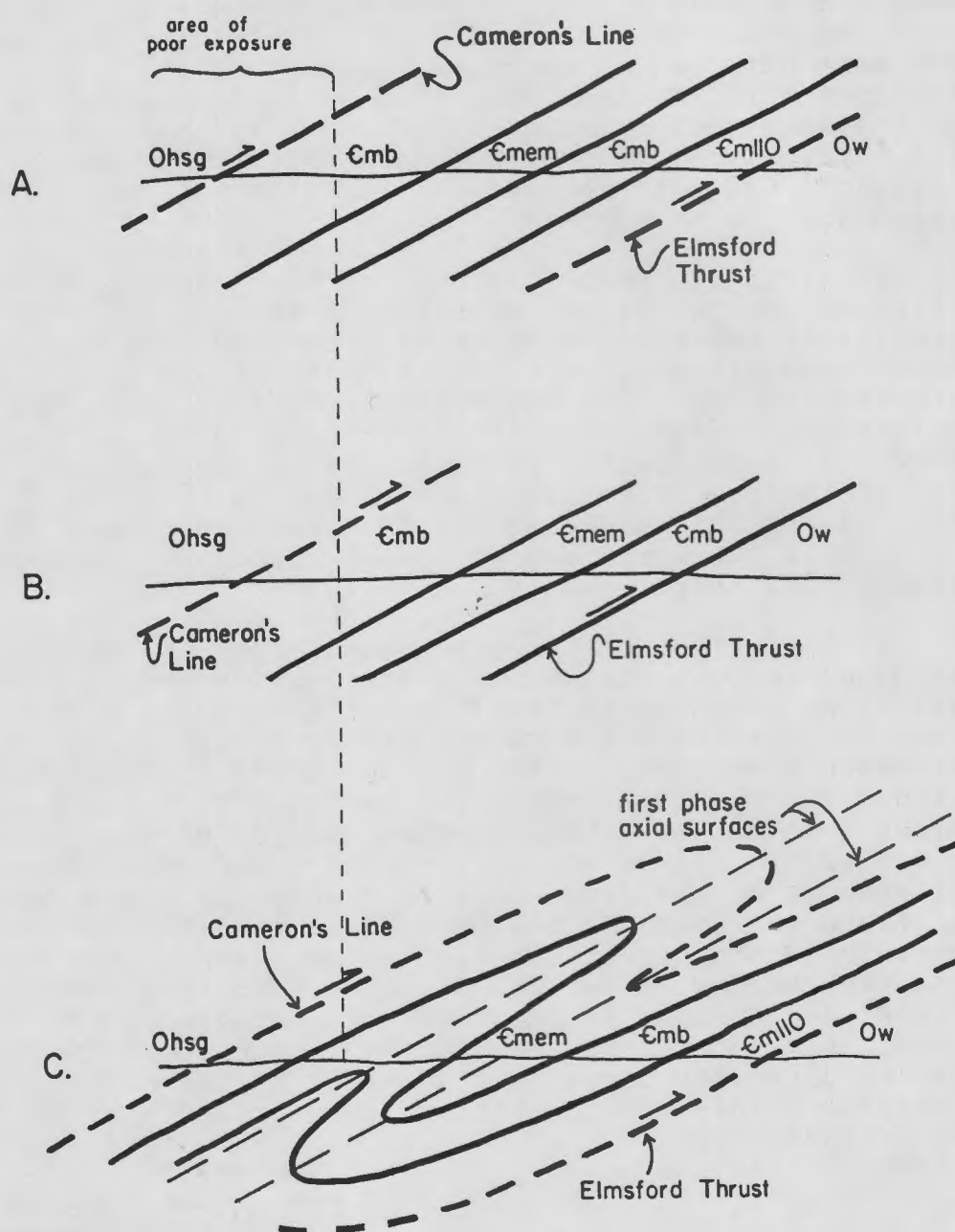


Figure 16. A) Simple structural interpretation. B and C) Alternative structural interpretations. See text for discussion.

METAMORPHISM

The formation of the schist, therefore,
took place under mass-mechanical
conditions in the zone of ana-morphism
- Fettke, 1914, p.214

INTRODUCTION

The rocks of Central Park have been affected by several phases of Paleozoic regional metamorphism. Mineral assemblages and textural relations observed in thin sections of pelitic schist and amphibolite have been studied to determine the metamorphic history. Textural relations in the Hartland Formation rocks and Manhattan Formation rocks are indistinguishable, suggesting that both units have undergone the same metamorphic history beginning after the Hartland Formation rocks were emplaced above the Manhattan Formation rocks along Cameron's Line.

MINERAL ASSEMBLAGES

Besides muscovite and biotite, garnet and kyanite are the dominant metamorphic minerals in pelitic schist, with sillimanite and staurolite less commonly observed. Based on textural relations observed in thin section, some of which are presented below, it is believed that two main phases of metamorphism have affected these rocks. An early garnet-sillimanite grade metamorphism was followed by a kyanite-staurolite grade metamorphism which locally reached conditions of the lower sillimanite zone.

Garnet porphyroblasts are typically embayed and deformed, and appear to be a product of the early metamorphism. Garnet porphyroblasts locally contain abundant inclusions of quartz, hemo-ilmenite, biotite, muscovite, and sillimanite. Figure 17 shows an early sillimanite foliation preserved inside a large garnet porphyroblast. While sillimanite is locally observed as inclusions in garnet, kyanite and staurolite inclusions within garnet are very rare even when they are abundant in the rock matrix, supporting the assumption that garnet and sillimanite growth predate kyanite and staurolite growth. A similar texture is observed inside a sharply zoned tourmaline grain in sample CP24 (Table 5); fine sillimanite inclusions are preserved in the dark green inner zone, while the aluminosilicate in the light green outer zone and in the rock matrix is kyanite.



Figure 17. Sketch of part of thin section of sample CP47 (Table 5) from the Schist and Granulite Member of the Hartland Formation. The large garnet (G) has aligned inclusions of early sillimanite (Si, black needles in garnet). Late staurolite (stippled) and kyanite (K, cross-hatched) appear to be eating into the garnet. B=biotite (close-ruled); M=muscovite (wide-ruled); Q=quartz; solid black=opaques.

Table 8. Mineral assemblages in pelitic schists.

All samples contain the following, either alone or plus one of the other numbered assemblages:

Quartz-oligoclase-biotite-muscovite-

- 1) -kyanite
 - 2) -garnet
 - 3) -kyanite-garnet
 - 4) -kyanite-garnet-staurolite
 - 5) -kyanite-garnet-staurolite-sillimanite
 - 6) -kyanite-garnet-sillimanite
 - 7) -garnet-sillimanite
 - 8) -garnet-staurolite
-

Table 9. Mineral assemblages in amphibolites.

All amphibolite samples contain the following, plus one of the numbered assemblages:

Hornblende-plagioclase(oligoclase-labradorite)-quartz-pistacite-

- 1) -biotite
 - 2) -sphene
 - 3) -biotite-sphene
 - 4) -biotite-sphene-rutile
 - 5) -augite-sphene-rutile
 - 6) -sphene-rutile
-

The late phase of metamorphism was dominated by fresh-looking, subhedral, millimeter-sized kyanite grains growing in lenses, layers, and aggregates (Fig. 18). Clean, subhedral staurolite is not so common as kyanite, but the two phases appear to have grown in equilibrium. Kyanite and staurolite grains are observed consuming anhedral, ragged garnet grains (Fig. 17), further evidence that kyanite and staurolite growth postdate garnet growth. In some sections there are clean, euhedral garnet grains or overgrowths on early deformed garnet poikiloblasts, indicating that some garnet has grown during the late phase of metamorphism.

Sillimanite is locally observed in the schist matrix in apparent equilibrium with kyanite (Fig. 19), suggesting that in some areas the late phase of metamorphism may have reached sillimanite grade. Decisive textural relations

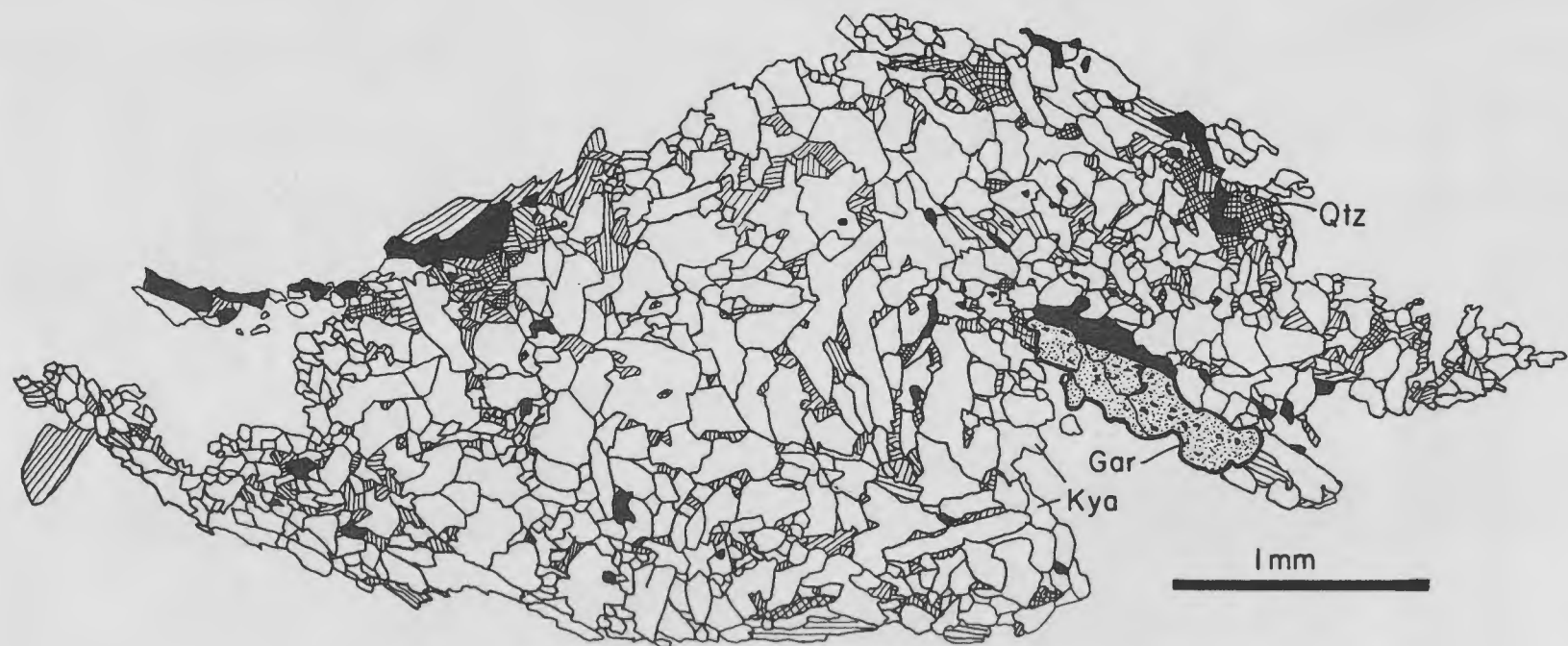


Figure 18. Sketch of a kyanite aggregate in thin section. From sample CP58 (Table 5) of the Schist and Granulite Member of the Hartland Formation. Gar=garnet (stippled); Kya=kyanite (unpatterned); Qtz=quartz (cross-hatched); solid black=opaque; muscovite and biotite are ruled.

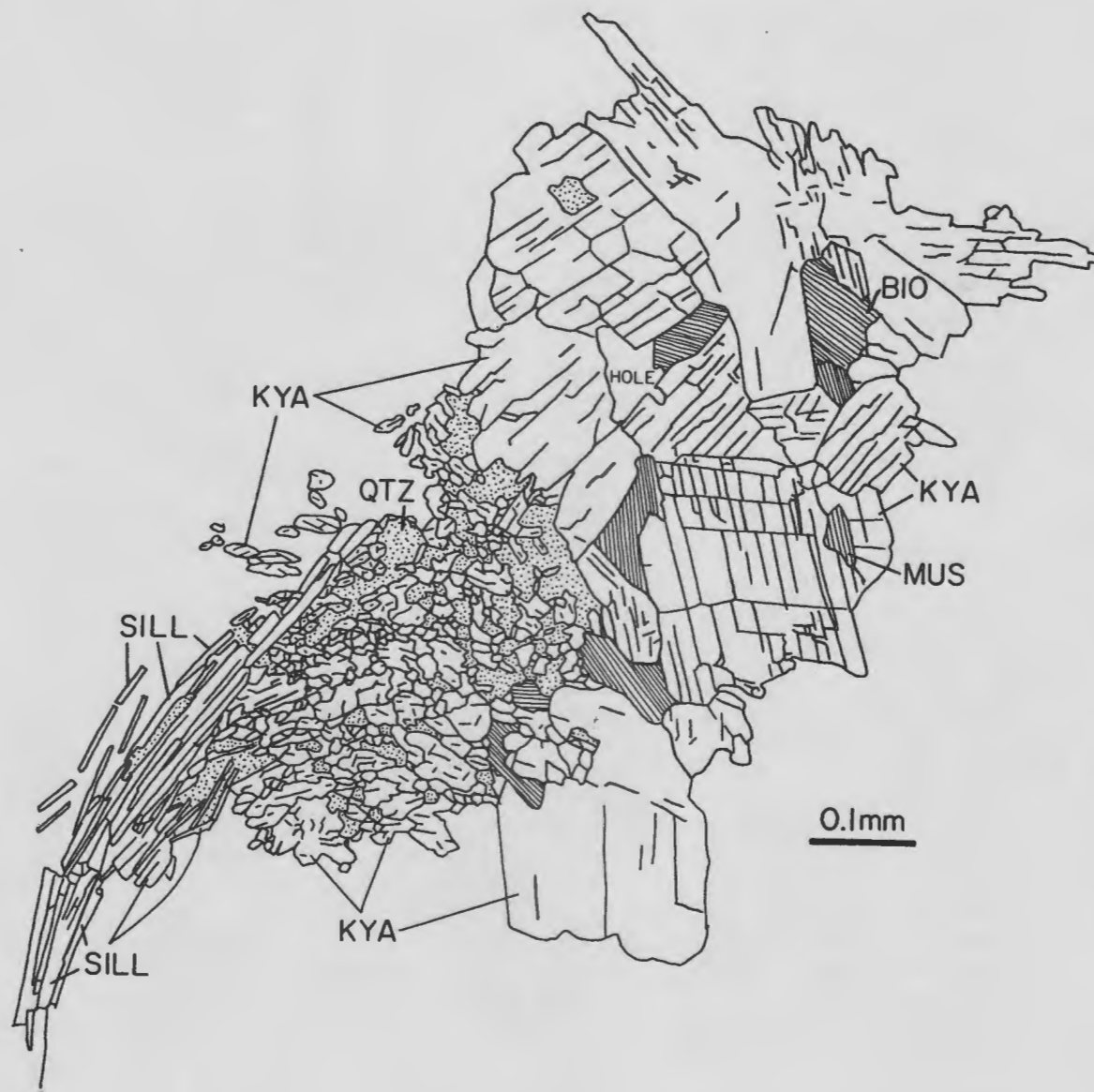


Figure 19. Sketch of part of thin section of sample CP31 (Table 3) from the East Meadow Member of the Manhattan Formation, showing textural relations between kyanite and sillimanite. Sillimanite (SILL) occurs as elongate grains at left. Kyanite (KYA), shown with cleavage, occurs as coarse, subhedral grains at top and right, and as a fine-grained mass with quartz at center. QTZ=quartz (stippled); biotite (BIO) and muscovite (MUS) are shown ruled; HOLE=hole in section.

like those shown in Figure 17 are rare, and it is usually very difficult to establish whether sillimanite is early or late. Fibrolite is commonly observed growing in sprays in muscovite (Fig. 20), but it is uncertain whether this is early fibrolite overgrown by late muscovite or if it is late fibrolite nucleating in muscovite.

In sample CP16 (Table 2) it appears that early sillimanite has survived in folded aluminous layers composed mainly of folded sillimanite and undeformed kyanite. At a nearby outcrop an 8-inch sillimanite crystal in schist is visible, aligned with the first-phase foliation. An immersion mount of a powdered sample of this crystal shows it to be composed dominantly of sillimanite, with minor proportions of quartz and kyanite which may be filling cracks. A thin section of schist from this outcrop has a 10% modal abundance of kyanite and no trace of sillimanite (CP29, Table 2). The occurrence of the giant sillimanite crystal in kyanite schist is puzzling, as is the distribution of kyanite and sillimanite in general. It is by no means systematic, and it is an aspect of Central Park geology which warrants further study.

KYANITE AGGREGATES

Aluminosilicate aggregates in pelitic schist are found worldwide: in Central Park and throughout the Manhattan Prong; the Adirondacks; Rangely, Maine (Foster, 1981, 1982); Ireland (Yardley, 1977); the Scottish Highlands (Chinner, 1961); British Columbia (Pigage, 1982); central Massachusetts (Robinson, 1963); and in the Himalayas. Their origin is poorly understood. The aggregates in Central Park are particularly interesting because all of the references above describe sillimanite segregations, but aluminosilicate nodules in the Park are almost pure kyanite (Fig. 18).

The presence of kyanite aggregates is perhaps the most fascinating aspect of Central Park geology, not just because of their rarity, but also because similar nodules in rocks to the north and south of the area consist of sillimanite. In the White Plains area to the north, aggregates in the Manhattan Formation and the Hartland Formation are composed of sillimanite (Hall, in press). Nodules on Manhattan Island north of the Park consist dominantly of sillimanite (Merguerian and Baskerville, 1986).

There is no very good evidence as to the history of the nodules. They may be primary aluminous concentrations which have later been metamorphosed, or they may have been

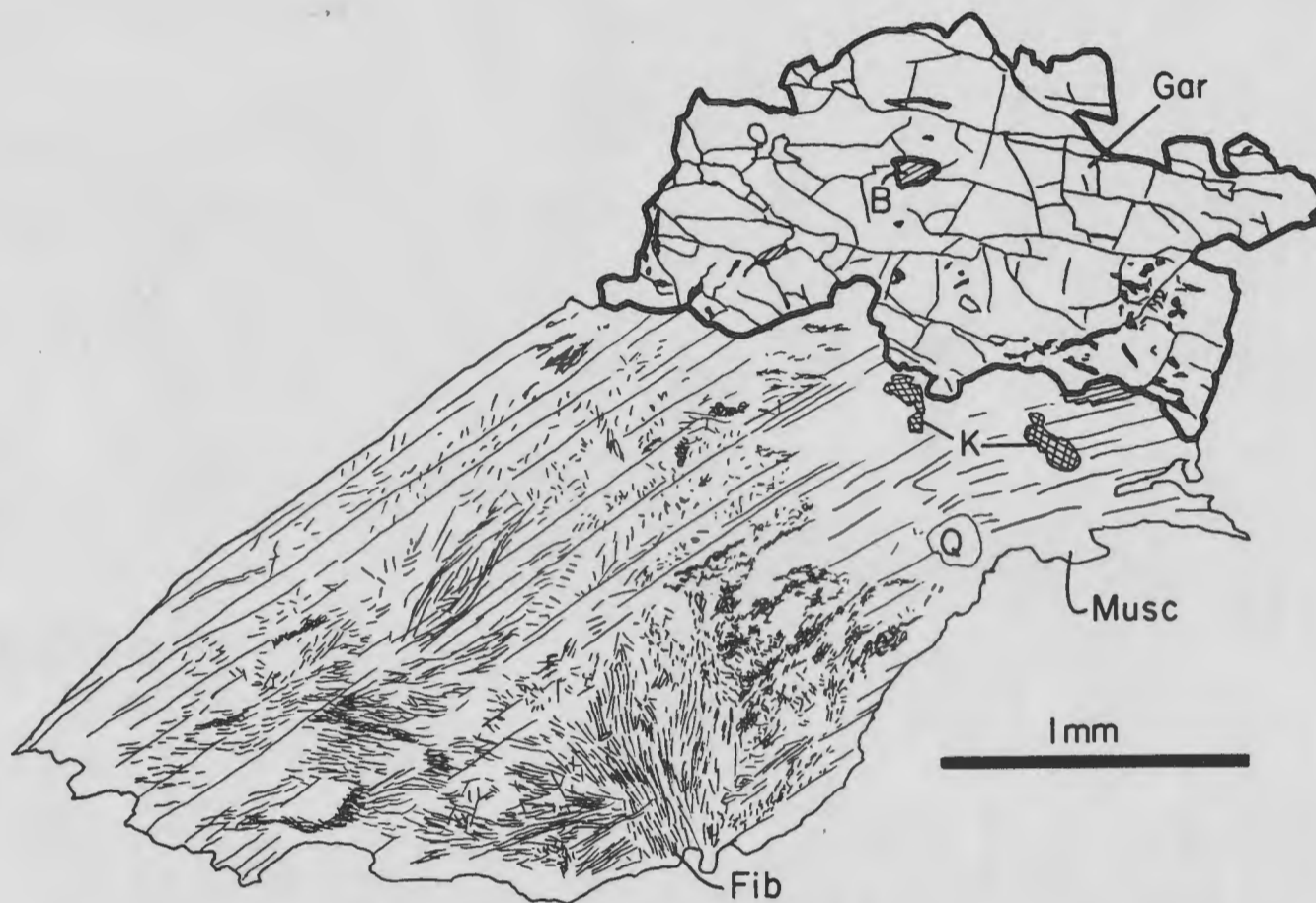


Figure 20. Sketch of part of thin section of sample CP28 (Table 5) from the Schist and Granulite Member of the Hartland Formation. Muscovite contains abundant inclusions of fibrolite (Fib). A relatively clean, heavily cracked garnet (Gar, heavy outline) has inclusions of biotite (B, ruled) and opaque (black). K=kyanite (cross-hatched); Q=quartz; Musc=muscovite (cleavage trace shown).

formed during metamorphism. The segregation shown in Figure 18 has a vestige of garnet remaining, suggesting that the nodule may be a garnet pseudomorph. Yardley (1977) documented the formation of fibrolite aggregates after garnet. However, the presence of early garnet in kyanite aggregates in the Park is exceedingly rare, and the majority of garnet observed in thin section is not being replaced by kyanite. The nodules may have originally consisted of sillimanite and later been replaced by kyanite, but early sillimanite has not been observed in association with the nodules. Andalusite pseudomorphs ("andalumps", Robinson, in Hatch and others, 1983) weather to a lumpy surface similar to the Central Park nodules, and suggest a possible origin. However, neither trace andalusite nor andalusite morphology is observed in outcrop or thin section.

RETROGRADE EFFECTS

Coarse retrograde muscovite plates overgrow the foliation associated with the third phase of deformation and apparently postdate the late phase of metamorphism. However, not all coarse muscovite is late. It should be noted that there are coarse muscovite books which are aligned in the first-phase foliation and are folded by third-phase folds (Fig. 7).

Other retrograde effects include the replacement of biotite by Fe-chlorite and the alteration of plagioclase to sericite.

AGES OF METAMORPHISM

The early phase of metamorphism appears to have occurred synchronously with the first phase of deformation, based on the observation that the first-phase foliation wraps around early garnet porphyroblasts and that inclusions of elongate minerals within poikiloblastic garnets are aligned with the first-phase foliation. It is more difficult to establish a relative age for the late phase of metamorphism. Individual kyanite or staurolite grains are not observed to be deformed by third-phase folds, although kyanite-rich layers certainly are (Fig. 21).

Long and Kulp (1962) recognized two major thermal events in the Manhattan Prong based on K-Ar dates from various mica types. The early event at about 480 m.y. corresponds to the Ordovician Taconian orogeny, with the later event at about 360 m.y. during the Devonian Acadian orogeny. However, later work (Bence and Rajamani, 1972;

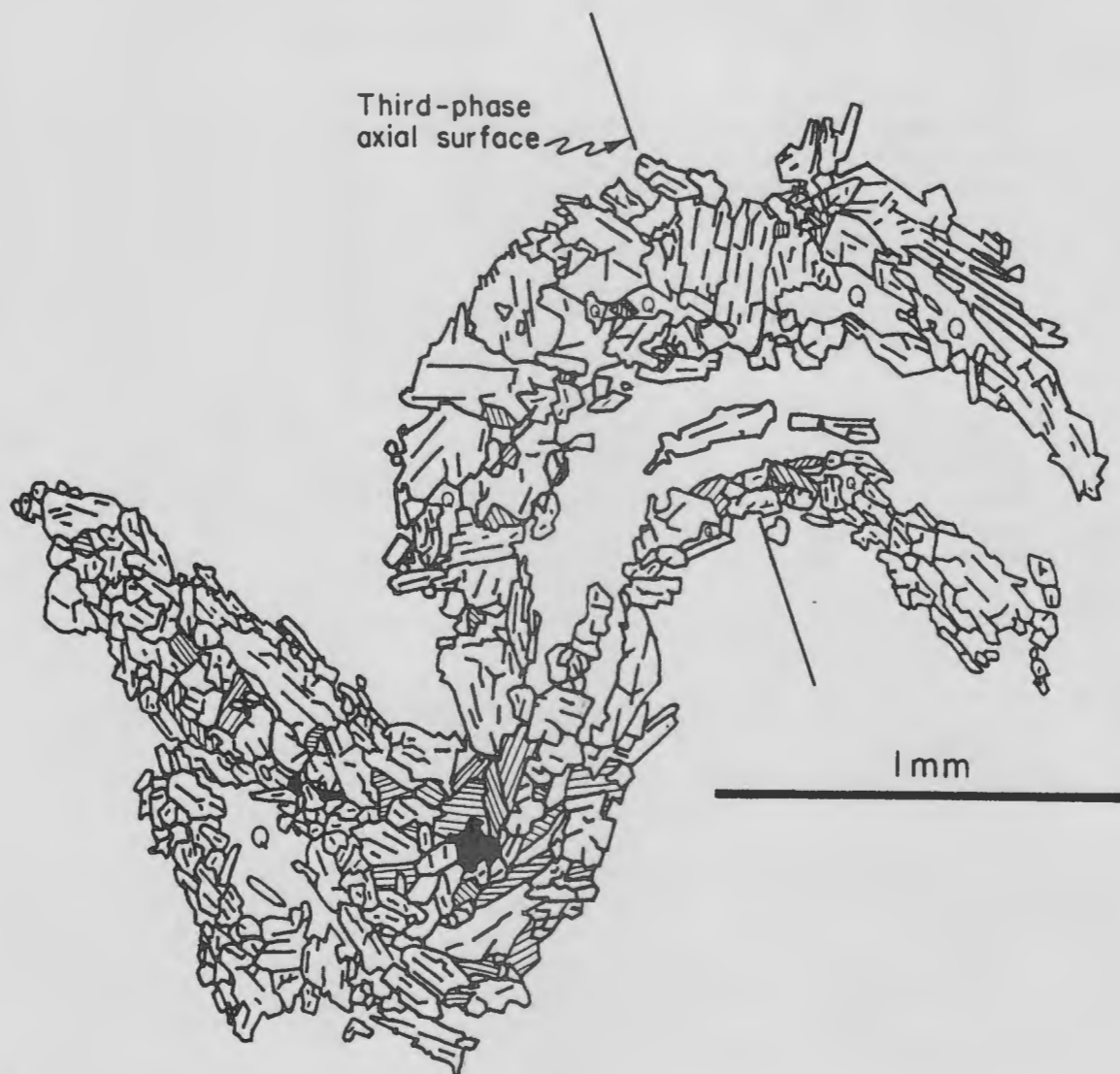


Figure 21. Sketch of part of thin section of sample CP47 (Table 5) from the Schist and Granulite Member of the Hartland Formation. Third-phase folds deform the kyanite-rich layers, but do not bend individual kyanite grains. Kyanite is shown with cleavage. Quartz (Q) is unpatterned; biotite and muscovite are ruled; opaque minerals are solid black. Blank areas between kyanite-rich layers are dominated by coarser-grained quartz and muscovite.

Dallmeyer, 1975) suggests that the Acadian ages reported by Long and Kulp (1962) reflect differential cooling following regionally pervasive Taconian metamorphism.

In the Croton Falls area Brock and Brock (1985) observed evidence for sillimanite-garnet-cordierite-perthite grade metamorphism during the Taconian orogeny, followed by muscovite-staurolite-kyanite grade metamorphism during the Acadian. This grade of Acadian metamorphism is in disagreement with studies by Ratcliffe and others (1982; 1983), and Sutter and others (1985) which suggest that there is no significant Acadian metamorphic overprint in southeastern New York.

Ratcliffe and others (1982; 1983) report that the Cortlandt Complex, a Taconian-age intrusion, cross-cuts a Barrovian regional metamorphic gradient. No metamorphism associated with post-intrusive features is observed, establishing a Taconian age for metamorphism. Ar/Ar ages from biotite and hornblende from the Cortlandt intrusives (Dallmeyer, 1975) yield undisturbed release spectra with average ages of 450-420 m.y., indicating that the effects of Acadian reheating were minimal.

In a study of Ar/Ar and K-Ar age data from western New England, Sutter and others (1985) conclude that the main metamorphism in the Manhattan Prong is Taconian in age, with little or no evidence for Acadian overprinting.

Based on the latter two studies, both phases of metamorphism appear to be Taconian in age. The early phase of metamorphism is associated with first-phase recumbent folds, and the proposed Taconian ages of both features are consistent. The age of the late phase of metamorphism is not conclusively established relative to the phases of deformation observed in the Park, but a pre-third-phase age is favored. The age of the third phase of folding may be either Taconian or Acadian, and the Taconian age for the late phase of metamorphism is consistent with either age for third-phase folds.

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GLACIAL STRIATIONS

Half of all the places where the furrows were noticed were in the middle portion of the island, in the line of the Eighth avenue from Sixtieth-street to 105th-street, where without exception the direction is north forty-five degrees west.

- Mather, 1843, p.209

Considering that a tremendous amount of rock outcrop in Manhattan has been covered by construction since Mather first studied the geology of New York in 1843, it is fortuitous that the area where he noted the best striae now lies within the Park (Eighth Ave. is now called Central Park West between 59th St. and 110th St.)

These striations, grooves, and furrows are best seen at the south end of the Park, especially in the outcrops around Heckscher Playground. These features were cut into the rock by boulders and gravel dragged along the bottom of glaciers during the last glaciation. Many of the erratic boulders found in the Park have been carried southeastward from the Palisades and are now perched atop schist outcrops.

The orientation of the striations on the outcrop marks the trend of glacial movement. The polarity of movement (whether SE or NW) can be deduced by observing the shape of the outcrops. Many outcrops have smooth northwestern sides and steep southeastern sides where they have been subjected to glacial plucking in the down-flow direction. 167 striae were measured and plotted on the map in Figure 22. In Figure 23 azimuth-frequency histograms are plotted by subareas in 5-degree increments. It appears that the transport direction at the north end of the Park is roughly S45W. South of the Reservoir the orientation of the striations takes a slight turn, trending more to the south.

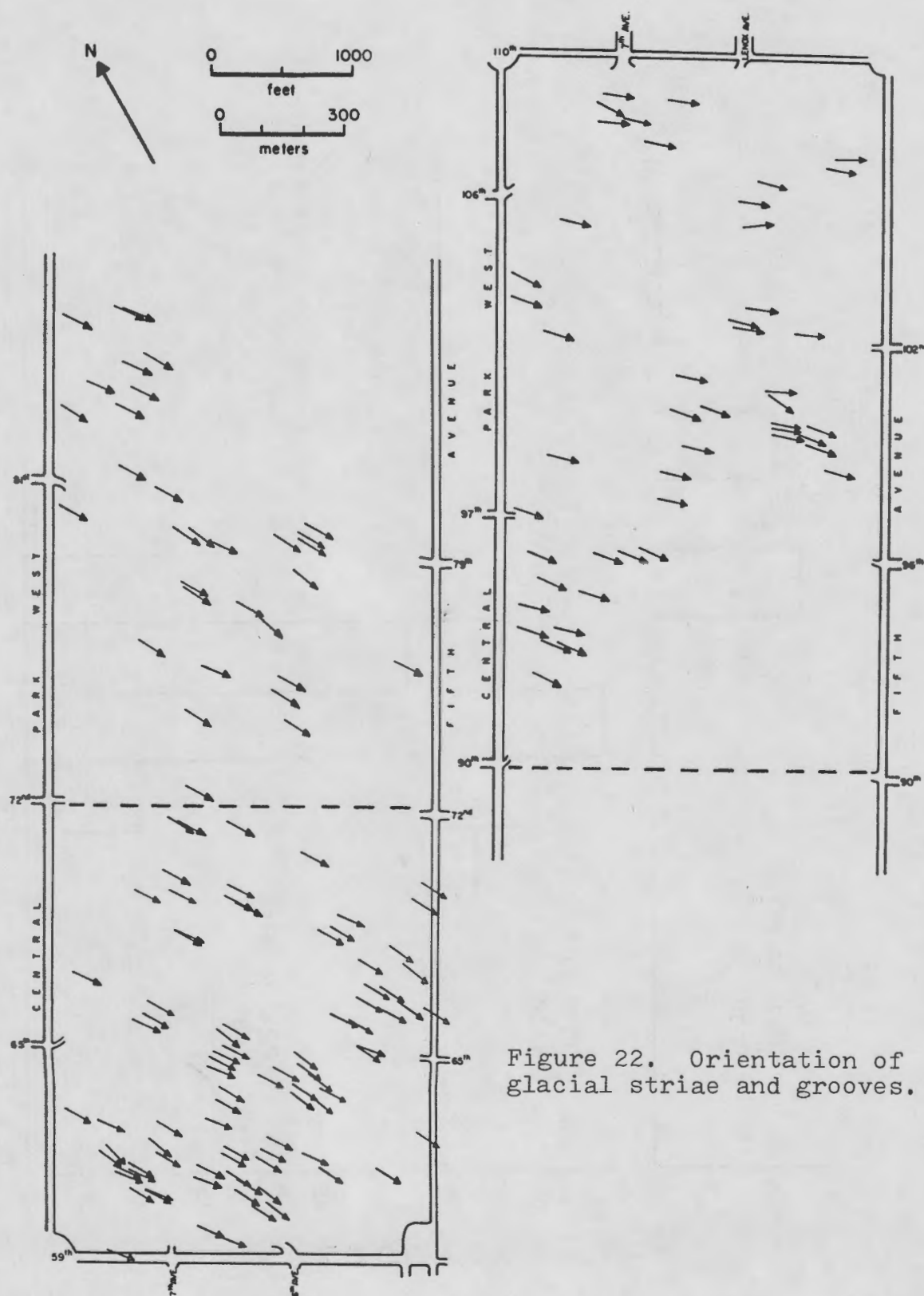
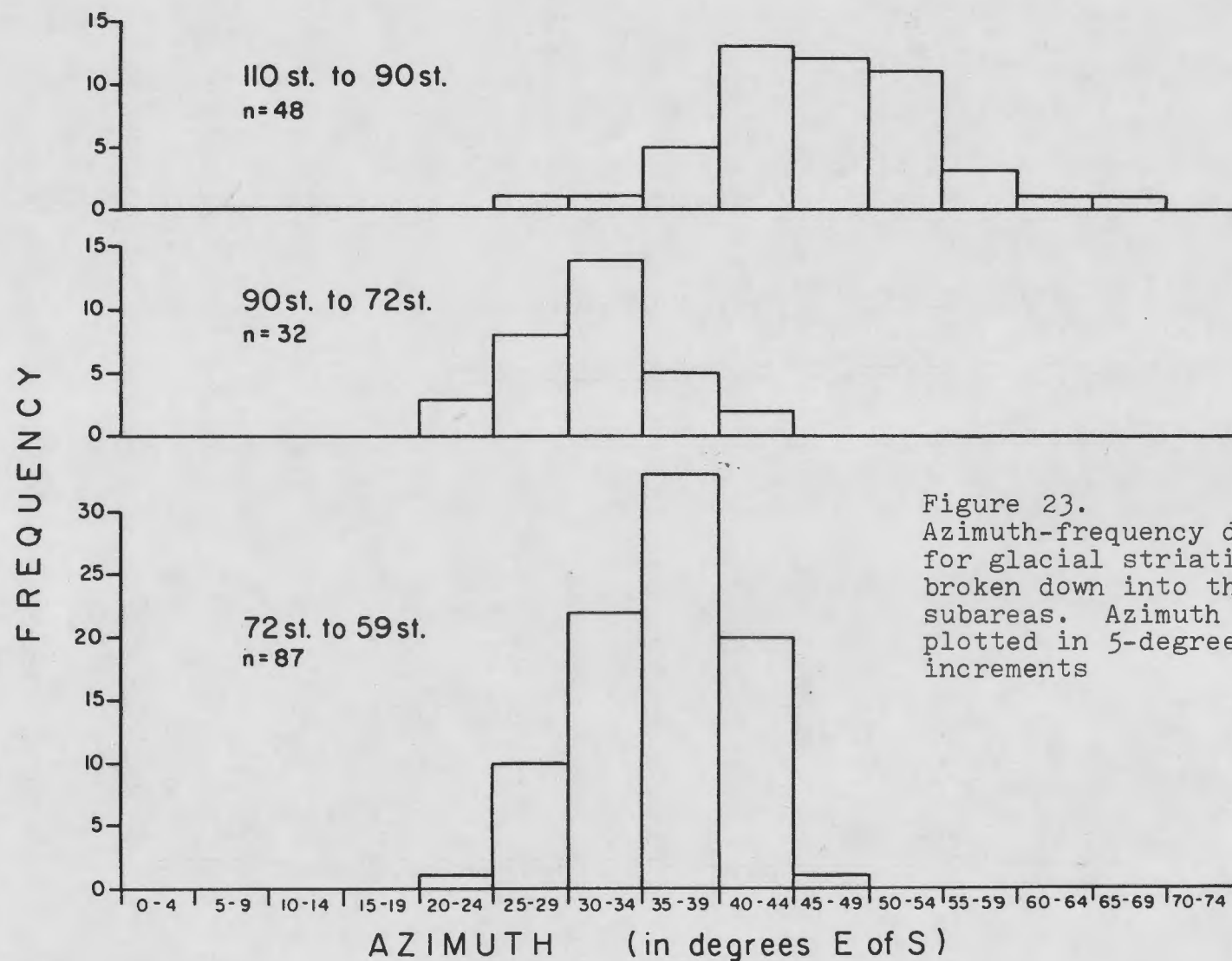


Figure 22. Orientation of glacial striae and grooves.



Office #61

Plate I. Geologic Map and Key to Symbols.

N

0 300
feet

0 100
meters

Base map grid is oriented N19°E.

Outcrop locations by Steven Reich and Bruce Toterka, 1965-1986.
Geology by Bruce Toterka, 1965-1986.

Intrusive Rocks

Granite and pegmatite. Granite is white and fine-grained, commonly with garnet. Pegmatite is white to pink, commonly with tourmaline and/or magnetite.

Metamorphosed Sedimentary and Volcanic Rocks

Hartland Formation

Early Middle Ordovician

Ohsg

Schist and Granulite Member. Gray-weathering, medium-grained, muscovite schist with abundant interbedded fine-grained quartzose granulite (stippled). Discontinuous amphibolite beds (black) are common.

Manhattan Formation

Blockhouse Member. See below.

Emem

East Meadow Member. Brownish-weathering garnet-kyanite schist with interbedded amphibolite (black).

Emb

Blockhouse Member. Knotty-weathering garnet-kyanite-magnetite schist with interbedded amphibolite (black).

Em10

110th Street Member. Brown-weathering garnet schist.

————— Lithic contact, accurately located

----- Lithic contact, approximately located

————— Form line of bedding and subparallel first-phase foliation

----- Granulite bed

----- Inferred form line of granulite bed

————— Amphibolite bed

----- Inferred form line of amphibolite bed

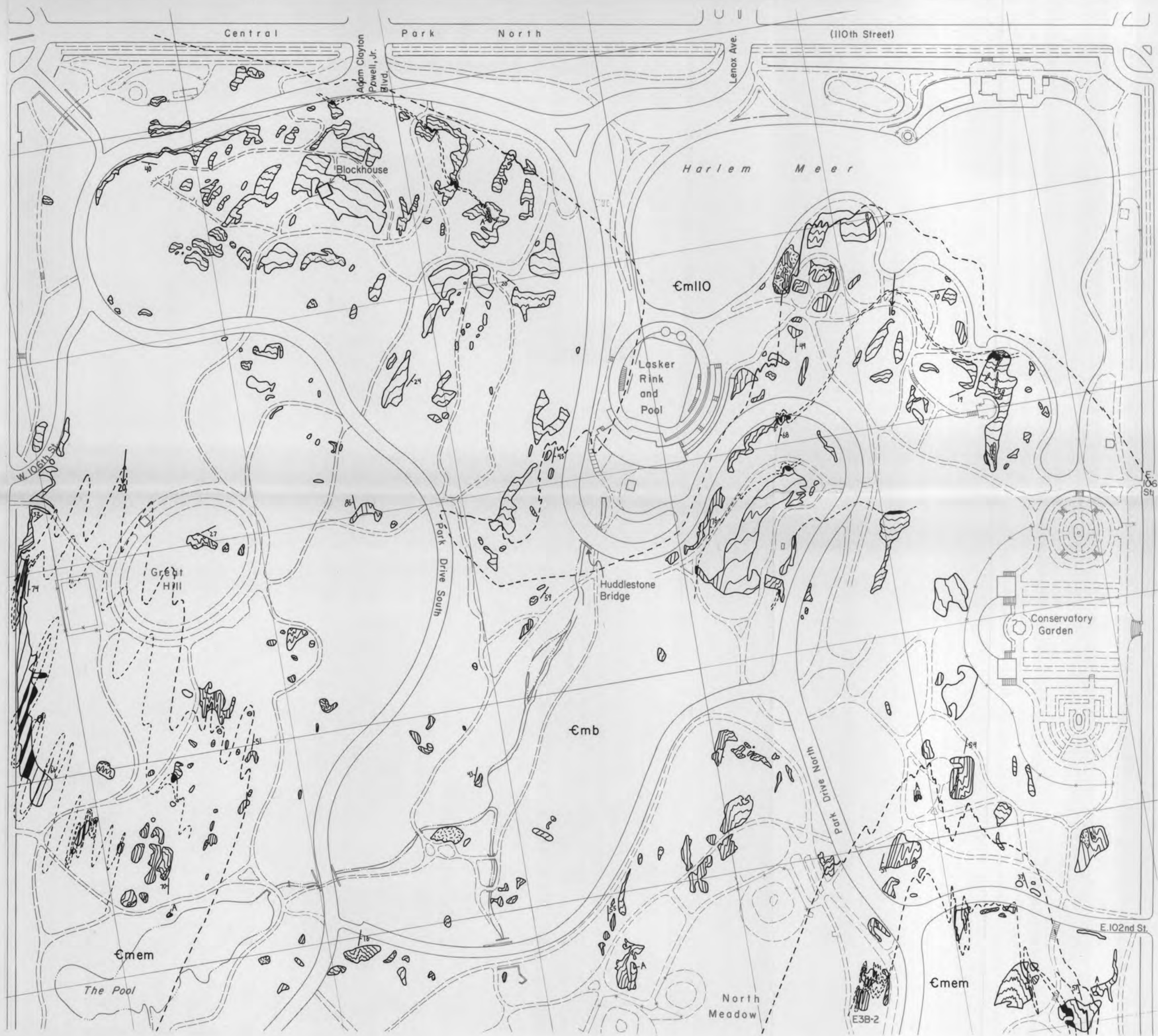
●-A Isolated amphibolite occurrence

76 Strike and dip of bedding and subparallel first-phase foliation

174 Trend and plunge of third-phase fold axis

— Fault, sense of movement indicated

E12A-9 Outcrop location referred to in text



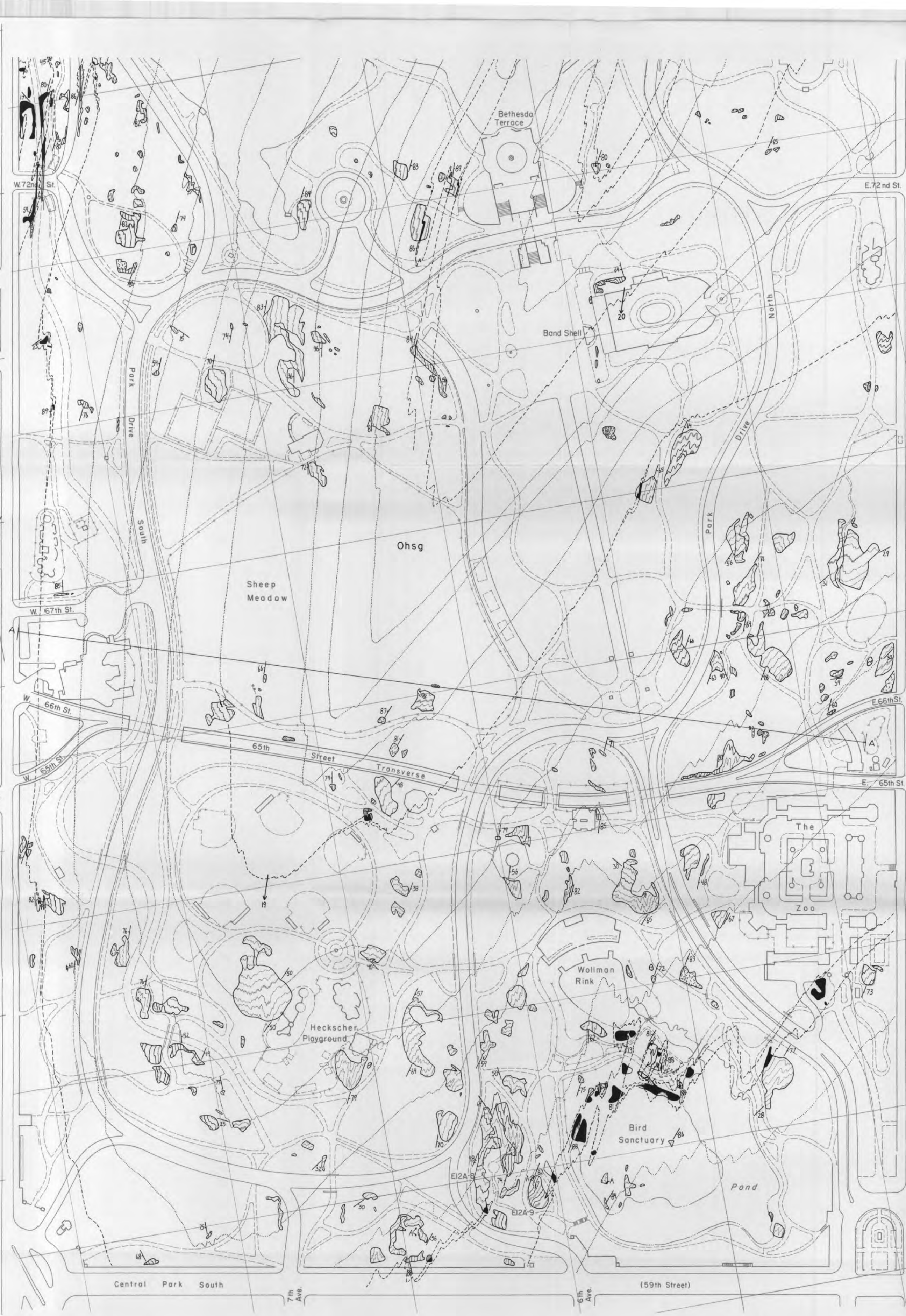
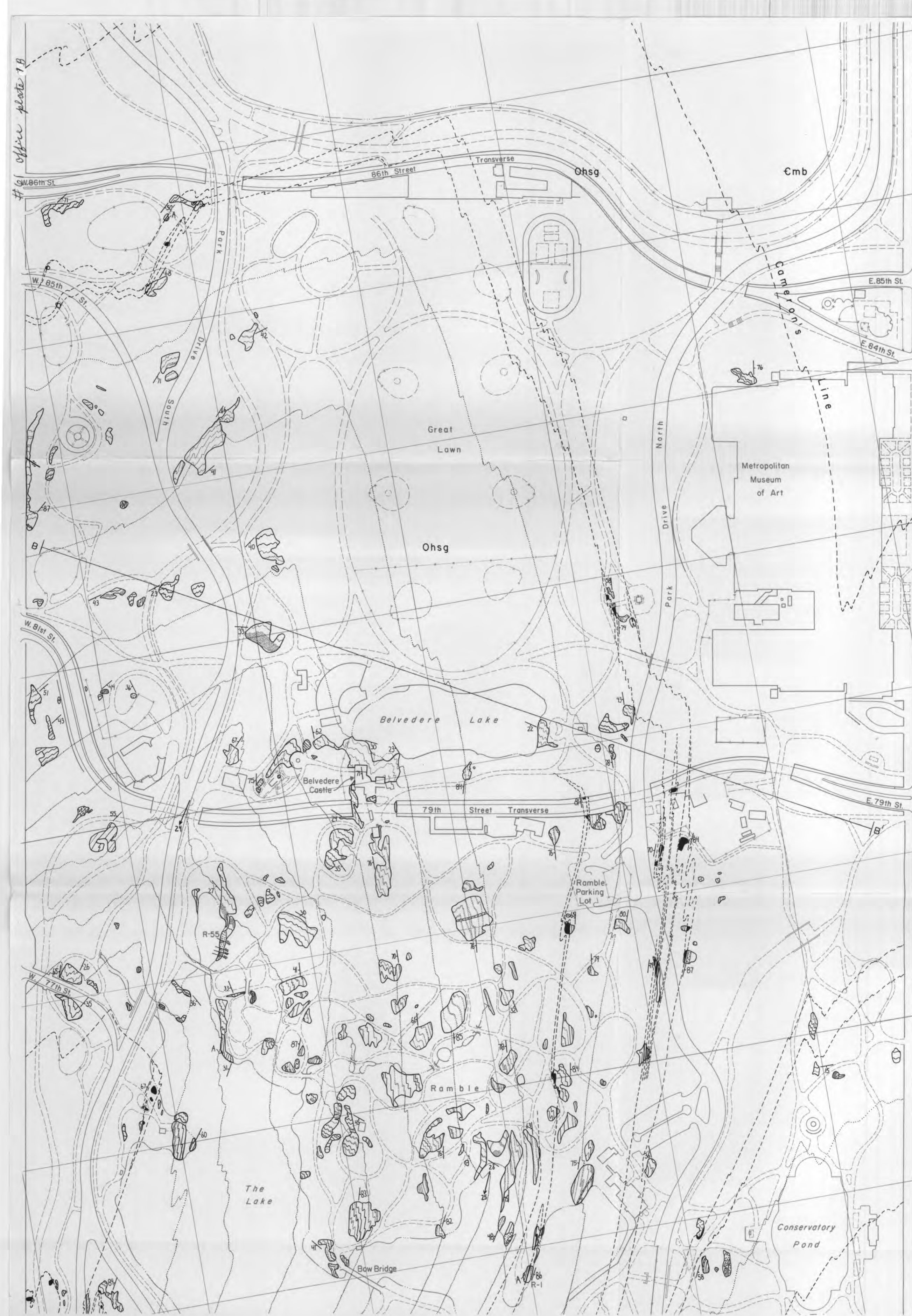
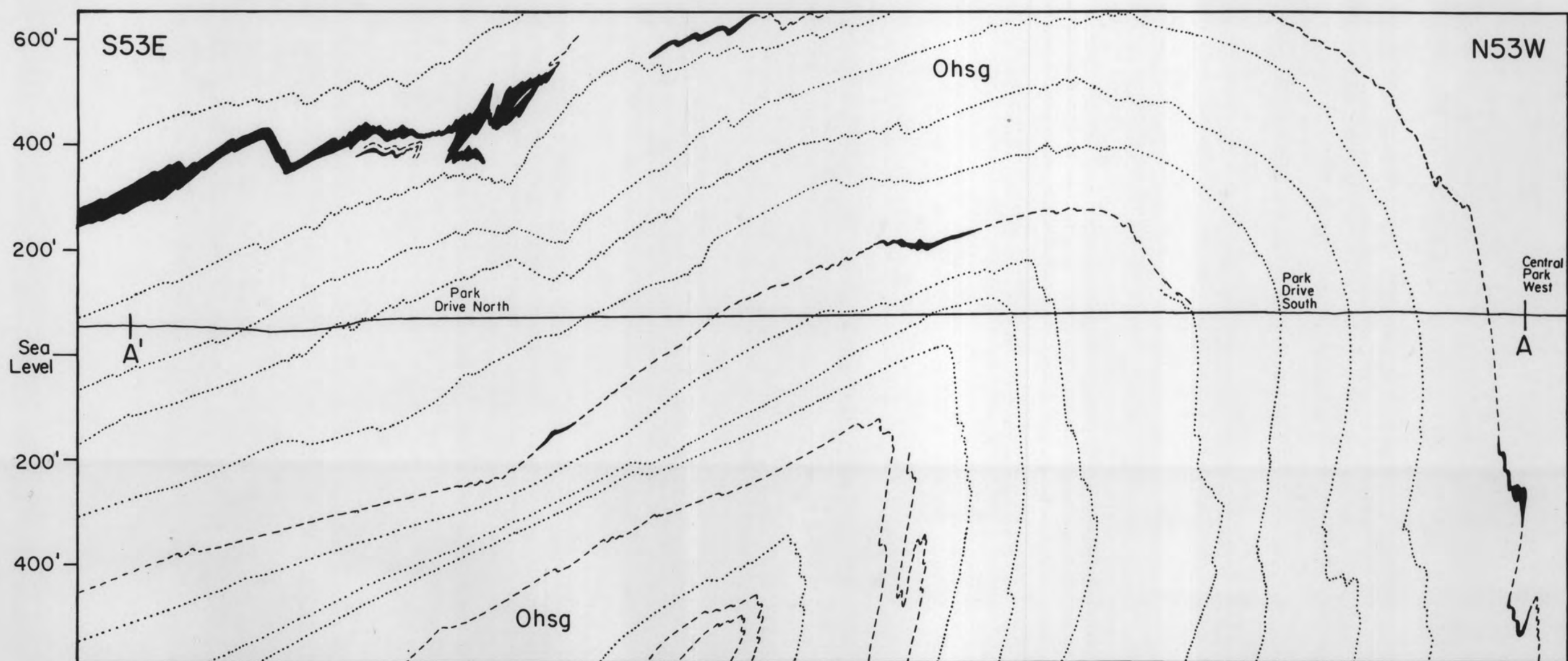


Plate 2. Geologic Cross Sections of Central Park.



Lines of cross section A-A', B-B', and C-C' are shown on Plate 1 (Geologic Map). Sections are extended beyond the east and west limits of the geologic map based on axial projection. Sections are arranged from south at top to north at bottom to facilitate down-plunge viewing along axes of third-phase upright folds. Hinges of major second-phase folds are indicated by "2".

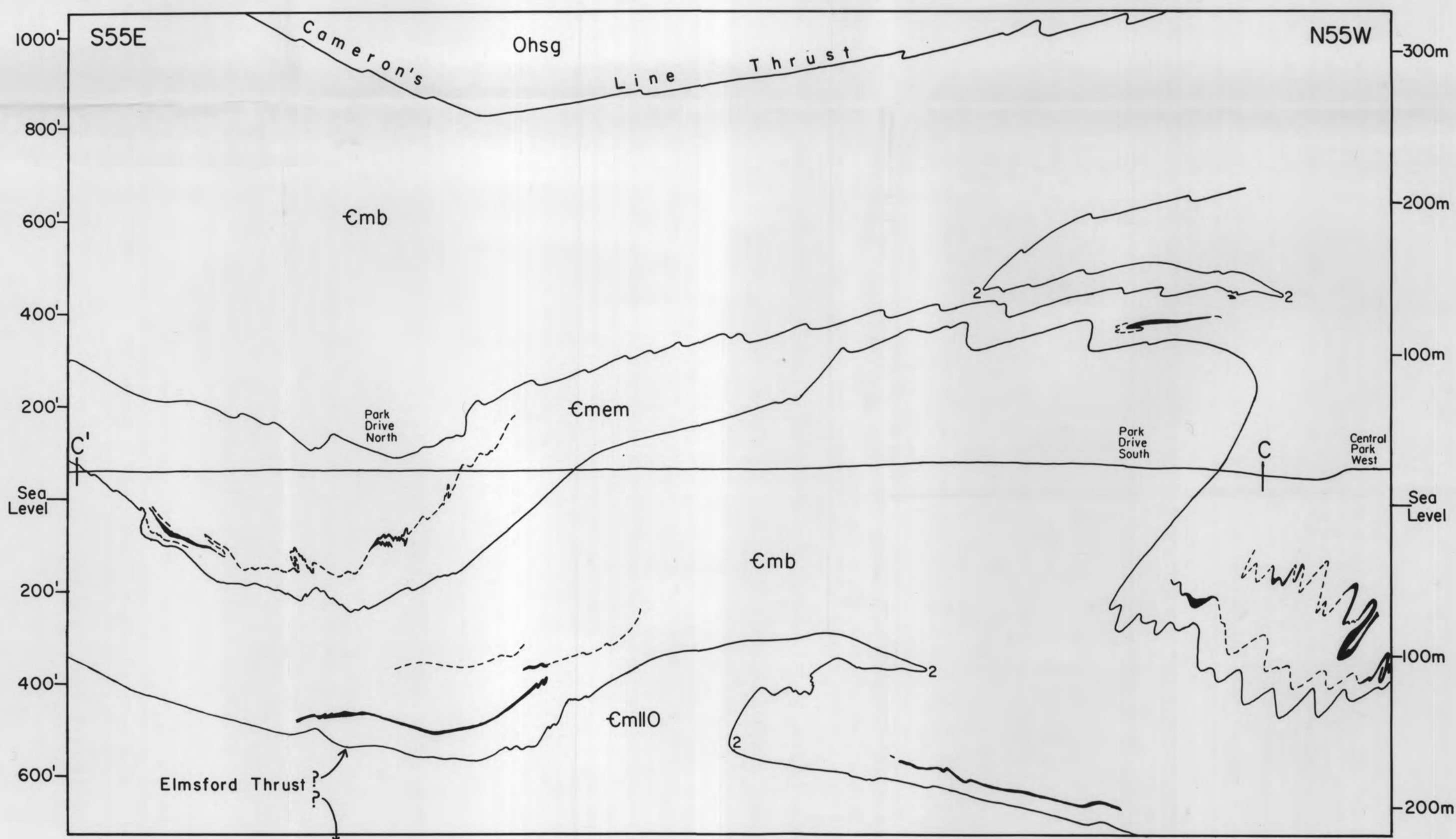
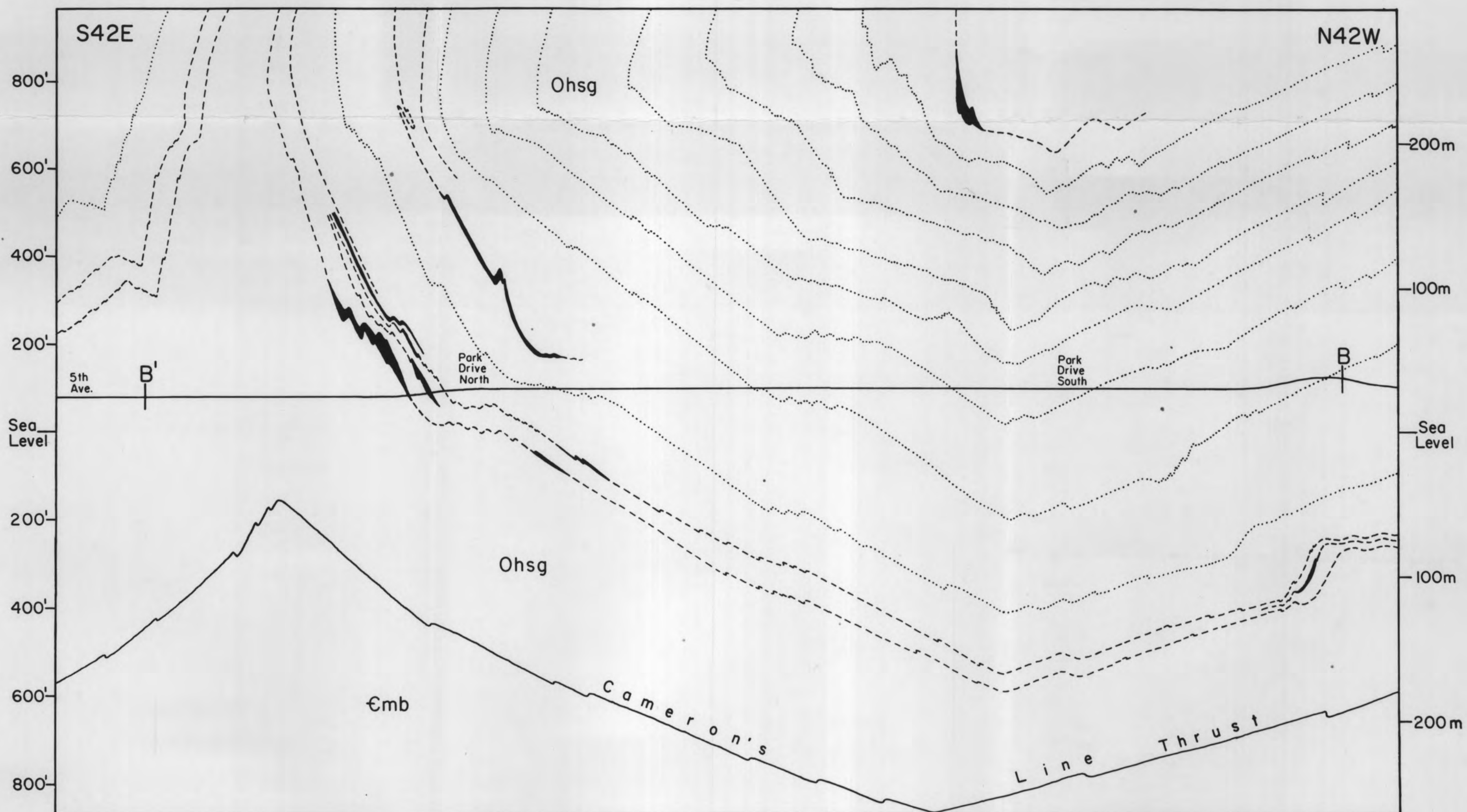
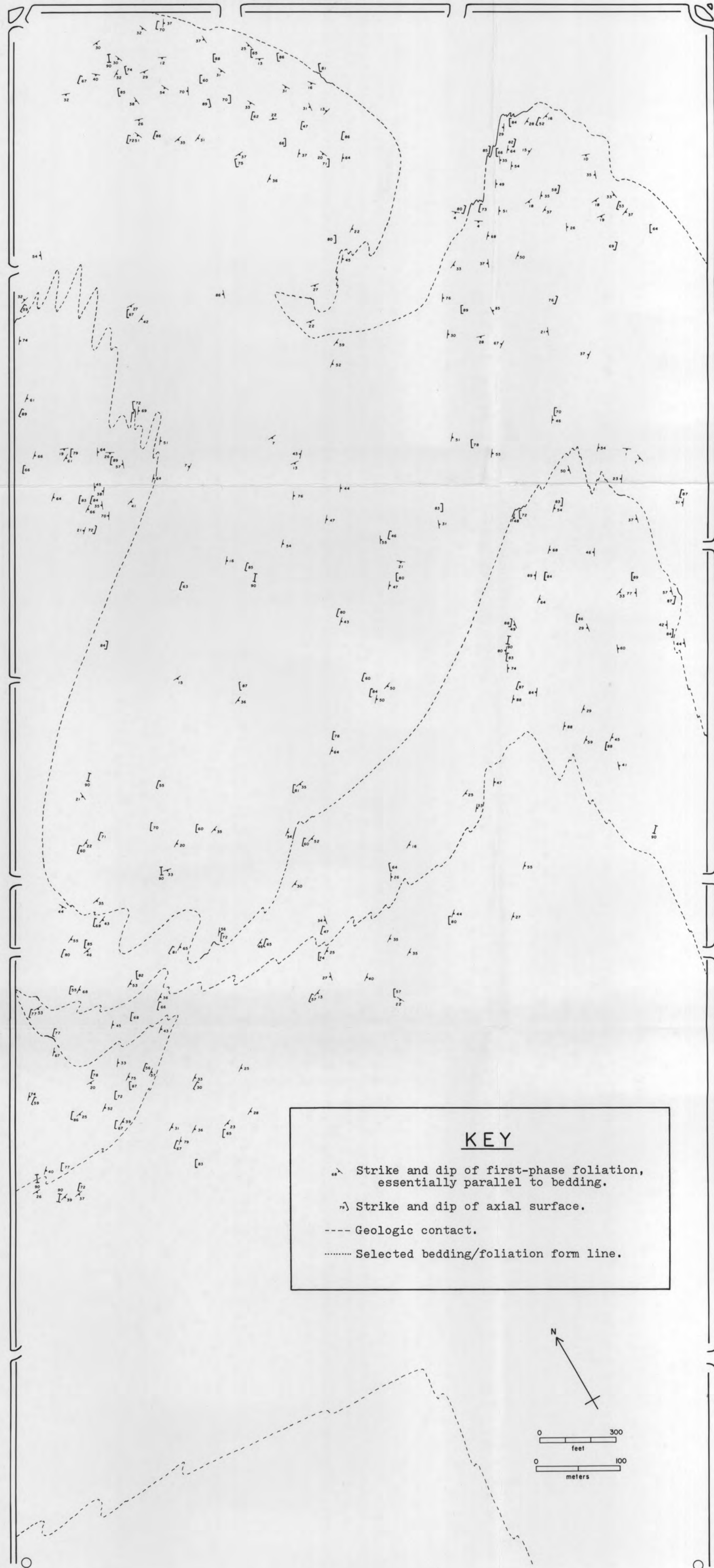
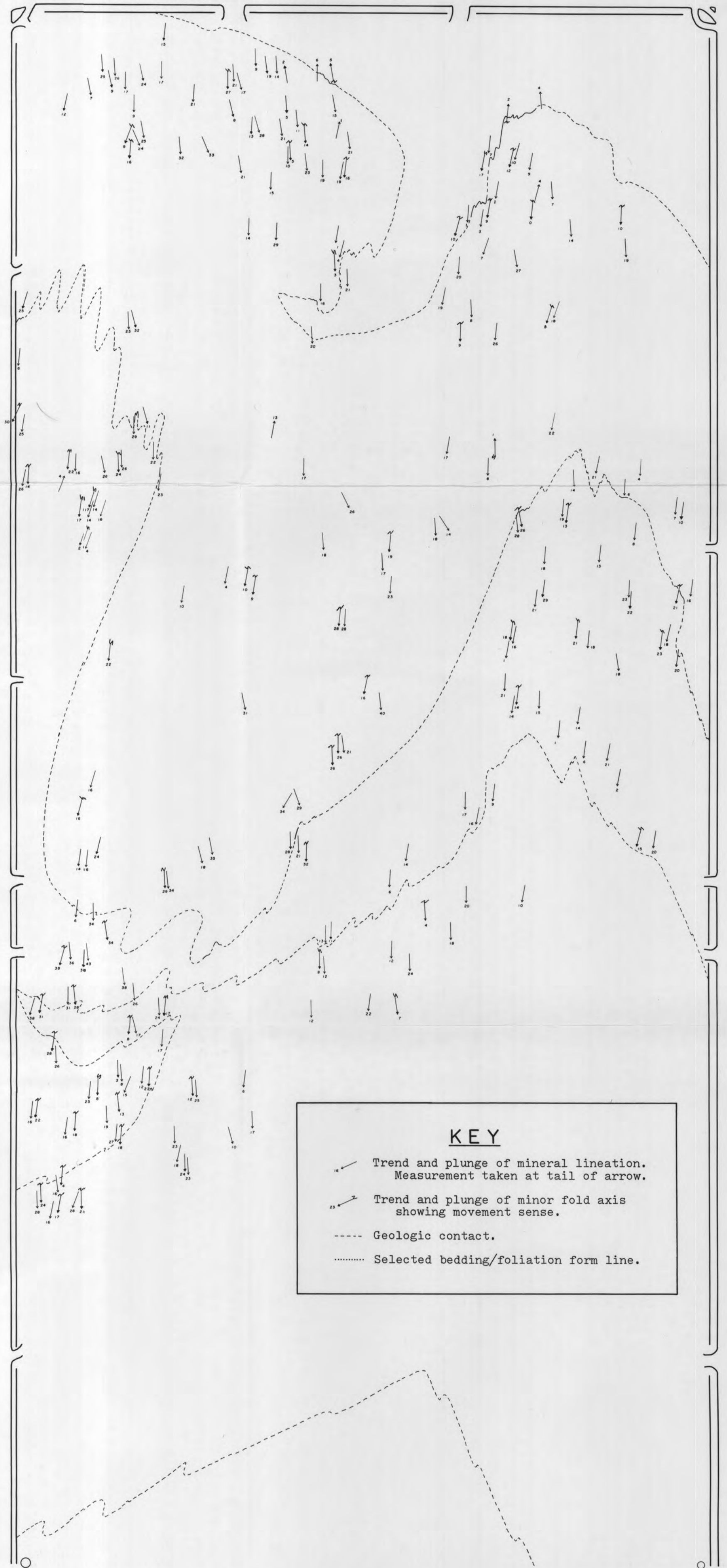


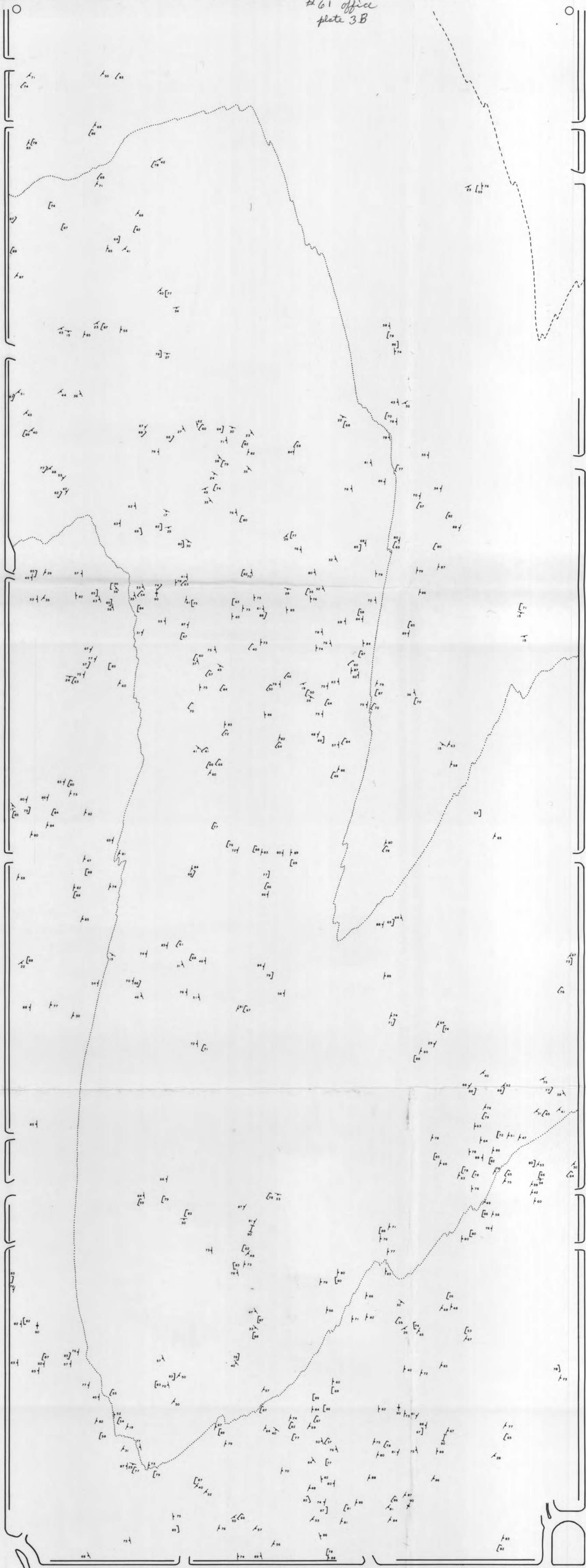
PLATE 3. PLANAR AND LINEAR STRUCTURAL FEATURES, CENTRAL PARK - PART A

PLANAR STRUCTURAL FEATURES



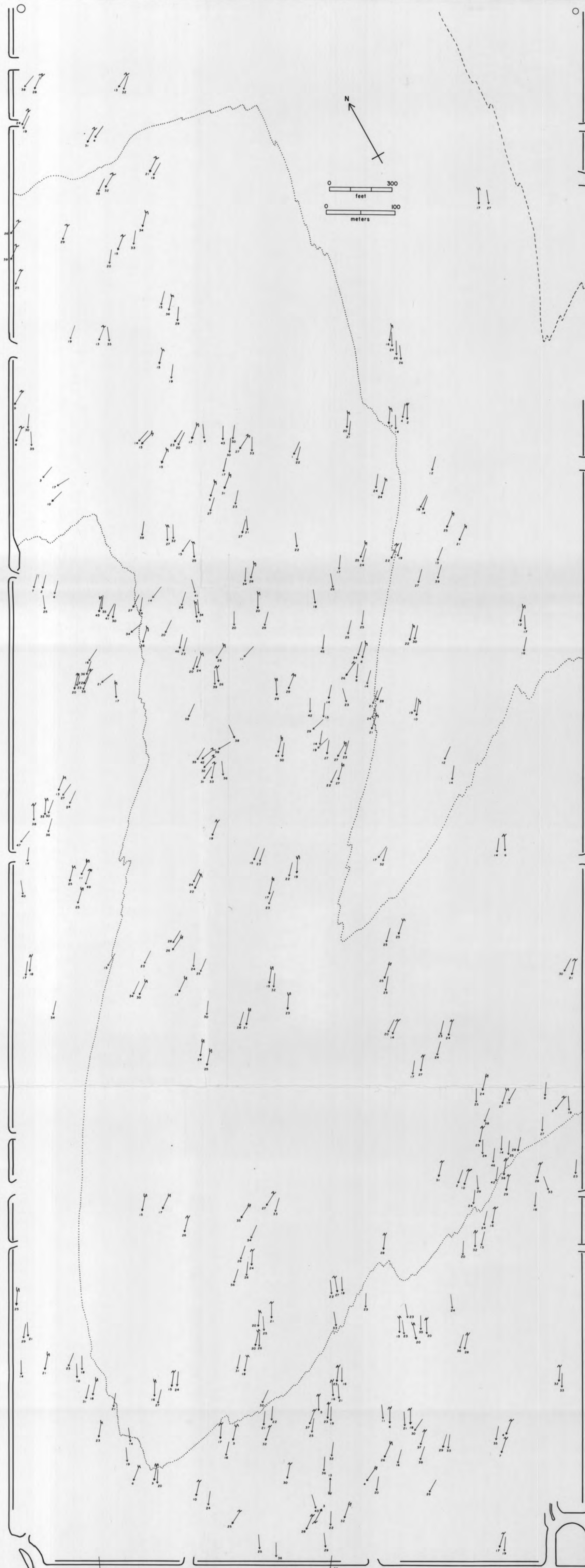
LINEAR STRUCTURAL FEATURES





PLANAR STRUCTURAL FEATURES

BRUCE TATERKA, 1987



LINEAR STRUCTURAL FEATURES

