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AIPG: TRIPS ON THE ROCKS

Southern Central Park, New York

20 May 2009

Field Trip Notes by:

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Geology of Southern Central Park, New York

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Logistics:
Departure from 59th Street and Central Park West @ 4:00 PM

INTRODUCTION

Today's walking trip to Central Park will cover only the southern part of this large area. We will begin near the zoo and swing around to the south and west, possibly ending opposite the American Museum of Natural History. In this guidebook, we review some of the history of the park itself, including its need and development, Robert Moses' reconstruction of the zoo in the mid-1930's as a tribute to his good friend, former Governor Alfred E. Smith, and many of the past geologic studies. We will depend considerably on CM's unpublished detailed studies carried out in 1982-1984.

Geologically, we shall concentrate on the metamorphic bedrock of the Taconic Sequence and on the glacially eroded features on the bedrock surface. In the bedrock, we will examine the basis for CM's mapping of Cameron's Line within southern Central Park. We will be "going in and out the window," so to speak, as we pass back and forth between the middle unit of the Manhattan Schist (Waramaug or Hoosac Formation equivalent) beneath the Cameron's Line overthrust and the Hartland Formation, which composes the upper, overthrust sheet. The trip will provide an adequate basis for demonstrating CM's subdivisions of the various schist units of New York City formerly lumped together as the Manhattan Schist formation.

In addition, we will focus on the glacial history of New York City as indicated by features developed on the crystalline bedrock by advancing Pleistocene ice. The rocky knolls within Central Park show dramatic effects of glacial erosion. The most-dominant features were caused by a thick glacier that flowed across Manhattan from about N30°W to S30°E. By careful study, however, it is possible to work out the effects of glacier(s) flowing from the NNE to SSW.

HISTORICAL BACKGROUND

In this section, we review some of the circumstances surrounding the origin and construction of Central Park, Robert Moses' 1934 rebuilding of the zoo, and some of the previous geologic work both in the park and in the general vicinity of Manhattan Island.

Central Park is rectangular in outline. It spans two and a half miles in length between 59th and 110th Streets and one-half mile in width between Fifth Avenue and Central Park West (Eighth Avenue). It covers roughly 840 acres in the midst of New York City, perhaps the most heavily engineered area in the world. According to the 1866 Guide to New York City (p. 31), "The Park was originally a bare, unwholesome suburb of the city, acres of it were naked of soil, and stagnant, marshy spots gathered the filth of bone-boiling establishments and pig-styes". Chronicles of the day reported that more than 5,000 squatters (outdoorsmen) lived on the terrain in shanties and hovels and that dog packs roved the area amidst the putrid smell of stables and the aforementioned pigsties and bone factories. Planned and constructed in the mid-1800s (Figure 1, on cover), Central Park rivals the well-known public parks of Europe and has provided an important rural aspect to recreational activities on Manhattan Island. The largest public park on the continent and known the world over for its natural botanical- and geological beauty and focus for a multitude of social- and cultural events since its construction, the story of Central Park is of historic interest to all students of our natural environment. As such, we here include a brief synopsis of the Park's unique story.

The History of Central Park

Drawing heavily from Cook (1869), the following section describes the planning and development of Central Park. In the early 1800s, Manhattan was a largely rural area with the greatest concentration of residential buildings located in the extreme southern part of the island. As late as 1825, the Battery and Bowling-Green were awash with trees and grasses with a small number of private homes and no shops or businesses. Population growth began in 1830 and a gradual changeover from a sparsely built city with open lots, water courses, and gardens to one having narrow streets with long blocks of closely built homes and small backyards. Soon, in response to population growth, the rapid incursion of hotels, warehouses, and offices, the residential character of the Battery area changed and homes were abandoned for areas farther north.

The need for open spaces was not felt by Manhattan dwellers at the time. The rural nature of much of the island, the close proximity to Staten Island (near total woodlands at the time) and Hoboken, New Jersey, satisfied the need for green, open spaces. The Battery remained a favored spot for leisure walks and abandonment and was often used for official receptions and military reviews. By the year 1848, the rapid increase in construction and population growth decreased the amount of open space. According to Cook (1869, p. 13), "There was no place within the city limits in which it was pleasant to walk, or ride, or drive, or stroll; no place for skating, no water in which it was safe to row; no field for base-ball or cricket; no pleasant garden where one could sit and chat with a friend, or watch his children play, or, over a cup of tea or coffee, listen to the music of a good band." Because of this dearth of potential amusement,

New Yorkers began to "go to the mountains" and the upstate areas of Saratoga and Newport were host to great numbers of Manhattanites able to drive away from the city.

At the time, the great cemeteries, including Mt. Auburn near Boston, Laurel Hill in Philadelphia, and Greenwood in New York, were all the rage for solitude and green beauty. According to Cook (1869, p. 15), "The truth is, people were glad to get fresh air, and a sight of grass, and trees, and flowers, with, now and then, a pretty piece of sculpture, to say nothing of the drive to all this beauty, and back again, without considering too deeply whether it might not be better to have it all without the graves, and the funeral processions. Of course, at first, the sadder purpose of these places was not so conspicuous as it soon became." These parks and pleasure grounds with an occasional tombstone seen between the trees did not last for long as people were just dying to get into the cemeteries. Again from Cook (1869, p. 15), "And then the tide turned, and fashion and pleasure looked about for a garden where death was not so frequent a visitor."

Impressed on their vacations by the public gardens and parks in England, returning New Yorkers were struck by the lack of such places in New York City. By 1850, articles addressing this issue were published in the leading newspapers and magazines about town. As such, a letter was sent by then mayor A. C. Kingsland to the Common Council on April 05, 1851. This letter (reproduced on the following page) was, at once, referred to the Committee on Lands and Places whose recommendation was for the Legislature to implement Mayor Kingsland's request by appropriating (taking for a reimbursement in layman's terms) that portion of New York Island known as Jones's Wood for the express purpose of constructing a public park.

Jones's Wood was a huge tract of land adjacent to the East River with few buildings but a few large mansions. The original plans for New York's public park proposed an area from Third Avenue to the East River and extending from 66th Street to 75th Street. The Legislature, in an extra session held in 1851, passed the Jones's Wood Park Bill on July 11, 1851 authorizing the city to acquire such land. Despite the passage of this bill, opposition was strenuous. The Board of Aldermen appointed a special committee (on August 5, 1851) to reexamine the legislative decree. This committee, consisting of Daniel Dodge and Joseph Britton, submitted a thorough report that, in the end, suggested a tract in the center of the island instead of Jones's Wood. The main arguments they cited were a more-central- and larger location, convenient access, and overall lower cost. The public report was well received and adopted by the Board of Aldermen and the Legislature passed an Act on July 21, 1853, authorizing the city to take possession of the land currently known as Central Park.

Five commissioners of estimate and assessment were appointed on November 17, 1853 by Supreme Court Judge William Mitchell and in three years were able to hear and decide upon the claims of 7,500 lots. Their final report to Judge Harris was dated October 4, 1856 and amazingly only one case in forty objected to the amount awarded. We wonder how long and through what legal wranglings would such an appropriation take place today! In any case, payment of $5,169,369.90 was made to landowners by the city for the land beneath Central Park (incidentally, $1,657,590 of this amount was paid by landowners adjacent to the proposed park in increased tax assessment in view of the benefits received by their proximity to the park!). As is true now, "The city giveth and the city taketh away!"

Mayor Kingswood's Letter to the Common Council, April 5, 1851

* To the Honorable the Common Council:—

GENTLEMEN—The rapid augmentation of our population, and the great increase in the value of property in the lower part of the city, justify me in calling the attention of your honorable body to the necessity of making some suitable provision for the wants of our citizens, who are thronging into the upper wards which, but a few years since, were considered as entirely out of the city. It seems obvious to me that the entire tongue of land south of the line drawn across the Park is destined to be devoted, entirely and solely, to commercial purposes; and the Park and Battery, which were formerly favorite places of resort for pleasure and recreation for citizens whose residences were below that line, are now deserted. The tide of population is rapidly flowing to the northern section of the island, and it is here that provision should be made for the thousands whose dwellings will, ere long, fill up the vacant streets and avenues north of Union Park.

The public places of New York are not in keeping with the character of our city; nor do they in any wise subserve the purpose for which such places should be set apart. Each year will witness a certain increase in the value of real estate, out of the city proper, and I do not know that any period will be more suitable than the present one for the purchase and laying out of a park on a scale which will be worthy of the city.

There are places on the island easily accessible, and possessing all the advantages of wood, lawn, and water, which might, at a comparatively small expense, be converted into a park which would be at once the pride and ornament of the city. Such a park, well laid out, would become the favorite resort of all classes. There are thousands who pass the day of rest among the idle and dissolute, in porter-houses or in places more objectionable, who would rejoice in being enabled to breathe the pure air in such a place, while the ride and drive through its avenues, free from the noise, dust, and confusion inseparable from all thoroughfares, would hold out strong inducements for the affluent to make it a place of resort.

There is no park on the island deserving the name, and while I cannot believe that any one can be found to advance an objection against the expediency of having such a one in our midst, I think that the expenditure of a sum necessary to procure and lay out a park of sufficient magnitude to answer the purposes above mentioned would be well and wisely appropriated, and would be returned to us fourfold in the health, happiness, and comfort of those whose interests are specially intrusted to our keeping—the poorer classes.

The establishment of such a park would prove a lasting monument to the wisdom, sagacity, and forethought of its founders, and would secure the gratitude of thousands yet unborn for the blessings of pure air, and the opportunity for innocent, healthful enjoyment.

I commend this subject to your consideration, in the conviction that its importance will insure your careful attention and prompt action.

A. C. KINGSLAND, Mayor.

The land for Central Park was first surveyed by a prominent engineer, Mr. Egbert L. Viele, and his report to the commissioners was dated January 1, 1857. Viele's plan was backed by then Mayor Wood but was not accepted for the final plan. The plan was deemed plain and commonplace and unbefitting the topography and ground to be worked. The roads were planned in an uninteresting manner (called "the Circuit" by Viele) nearly paralleling the existing roads of Fifth and Eighth Avenues and skirting the boundaries of the park. Transverse roads across the

surface of the park were also planned by Mr. Viele. On April 17, 1857 the Legislature appointed a new commission whose first act was to lay aside the Viele plan and to open a competition for new plans which were to be submitted by April 1, 1858. By a vote of seven ballots out of eleven, on April 21, 1858, a $2,000 award was given for the accepted plan (out of 33 plans submitted) called "Greensward" submitted by Frederick Law Olmstead and Calvert Vaux (Figure 2). We refer the interested reader to Cook (1869) and Laredo and Reed (1979) for additional information on the implementation of this plan and the construction of the park. Cook's work is fortified with many original engravings of structures, many of which stand today in the park. The photographs and text in Laredo and Reed are worthy complements to this brief discussion.
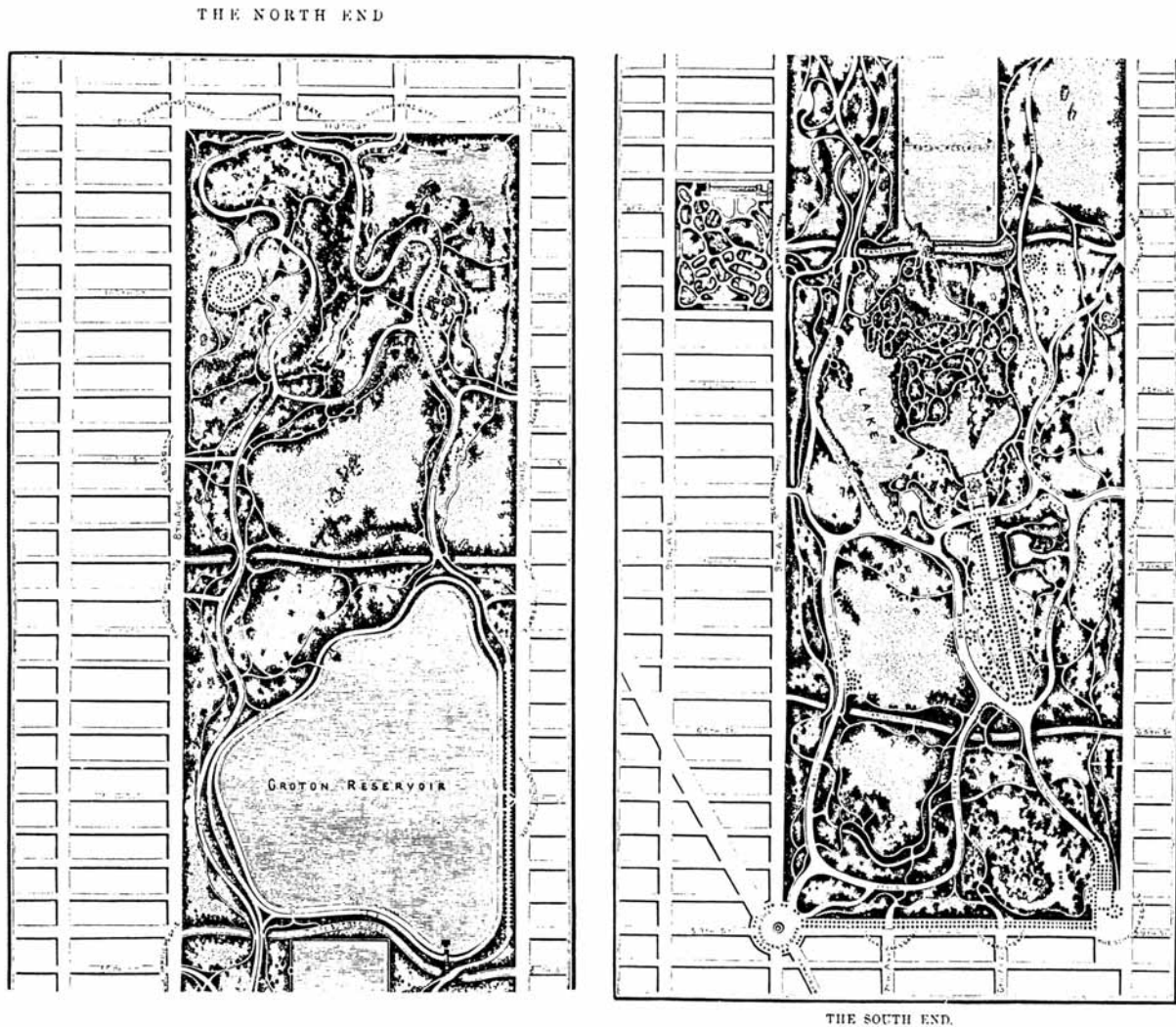
THE NORTH END

GROTON RESERVOIR

THE SOUTH END.

Figure 2 - Original "Greensward" plan of Olmstead and Vaux prepared in 1858. (Cook, 1869, p. 7-8.)

Rebuilding of the Zoo (1934): Robert Moses at his Finest

In the fall of 1933, New Yorkers were engaged in a hotly contested campaign for the office of Mayor. The old order, represented by Tammany Hall, was challenged vigorously by a so-called "fusion" candidate, Fiorello H. La Guardia. About two weeks before the election, Raymond Ingersoll persuaded Robert Moses to endorse La Guardia. Moses did so and many felt that his warm endorsement of La Guardia was what was needed to tip the balance in La Guardia's favor. After La Guardia had won the election, his first appointment was Moses as Park Commissioner. Moses set to work immediately, even before he was sworn in as Commissioner. In his first year in office, he carried out an incredible list of park improvements, most of them depending on federal funds that were being spent to mitigate the effects of the Great Depression. To give some idea of the scope of Moses' accomplishments and particularly his special efforts to rebuild the Central-Park menagerie as a tribute to his good friend and patron, former Governor Alfred E. Smith, we quote extensively from Robert Caro's (1974) book:

(p.347) Ch. 19. To Power in the City

"Moses dispatched teams of engineers to `inventory' New York City's parks--their acreage [incredibly no one knew their exact size (sic)], the buildings, paths, roadways, statues and equipment in them, the condition of these items and the type (sic) and amount of labor and materials that would be required to renovate them. He filed this information in a loose-leaf notebook kept atop his desk. By the time he was (sic) sworn in as Park Commissioner, the notebook was more than a foot thick, and he had a list of 1,800 urgent renovation projects on which 80,000 men could immediately be put to work.

"But renovation was only a small part of Moses' plan. Day after day during the bitterly cold November and early December of 1933, while the great city lay inert in the grip of its long malaise, Robert Moses was being chauffeured around it in the big Packard, Hazel Tappan beside him with a stenographer's note pad open in her lap. Twenty years before, as a young staffer at the Bureau of Municipal Research, Robert Moses had wandered around New York City `burning up with ideas, just burning up with them.'  Now Moses was not young--one of the days he spent in the big Packard was his forty-fifth birthday--but he was still burning.  `Sometimes it seemed to me that his voice never stopped,' Miss Tappan recalls. `Things just kept pouring out of him. I remember once we were downtown someplace and he wanted to see some underground garage-- for sanitation trucks or something--under a city building there to see if it would interfere with some plans he had for putting a park on the street near it and we started to go down this spiral ramp and it was getting darker and darker and he was still dictating. And finally it was almost pitch-black (sic) and he was still dictating. To this day I can see it getting darker and darker and that voice going on and on. Until finally I had to say, Mr. M! Mr. M! Wait a minute! I can't see!'

"By late December, the outline of his ideas for large-scale park construction (sic) projects was ready, and now, crowded into the Packard with him and Miss Tappan were his Long Island engineers. They came in relays. One crew would drive with him to certain parks--describing these trips, one engineer echoed Frances Perkins' words of two decades before, `Everything he saw made him think of some way it could be better'--and then that crew would go back to Babylon and translate his ideas into general engineering plans while another would head out with him to other parks.

"Relays were needed to keep up with him. `His orders just poured out,' recalls the engineer. `Bam! Bam! Bam! So fast that we used to all try to take them down at once so that when we got out to Babylon we could put them together and maybe get one complete list of everything he wanted. You'd start at dawn--hell, sometimes we'd start before dawn; I remember -- (p. 365) driving around Manhattan when everybody was still sleeping except the milkmen, maybe, and the cops on the beats. I remember once a cop really jumping when that big black car filled with men came around a corner in front of him--and by late afternoon, I can tell you, your head would be just absolutely spinning. But he'd still be firing things at you.' Didn't they break for lunch? `You didn't break for lunch when you were out driving around with Robert Moses.'

"Soon the engineers' concepts of his ideas were being presented for his approval.

"With few exceptions--City Hall is perhaps the most notable
-- the public works of New York City were hack work designed by hacks. But the men driving around with Robert Moses were not hacks. They included the unknown young architects, landscape architects and engineers--the Herbert Magoons and Earle Andrewses--responsible for Jones Beach and the other highly acclaimed Long Island parks. And they included Major Gilmore D. Clarke and Aymar Embury II. Clarke, designer of the Bronx River Parkway and other outstanding examples of highway beautification, was in 1934 the most famous (sic) landscape architect in the United States; he had been in the process of retiring from public work to accept lucrative private assignments. Embury, an architect, had designed Princeton University's classic Class of 1915 Dormitory and many of Long Island's most beautiful (sic) estates--parks in themselves. In 1934, he had waiting for him `more private business commissions than he could handle in a decade.' Moses persuaded Clarke and Embury to come to work on New York's parks.

"As had been the case with the famous architects who had gathered around him on the barren sand bar called Jones Beach a decade earlier, however, some of the men with him in the big Packard in 1934 had difficulty grasping the extent of his vision. When the plans came in for Riverside Park, where twenty years before, he had dreamed of a great highway along the water, a highway that would cover the ugly tracks and cleanse the West Side of Manhattan of the smoke and stench from the trains that ran along it, they left the tracks uncovered. The engineers told him that to cover them would add millions to the cost of the park development--for which at the moment there was (sic) almost no money at all in sight, not to mention the additional millions that would be needed to build the Henry Hudson Bridge across Harlem River Ship Canal and a parkway linking the bridge with the Saw Mill River Parkway. Moses told them to worry only about the plans; he would worry about getting the money for them.

"Down at his State Parks Council office at 80 Centre Street
-- Moses was never to have an office at the Arsenal and was to visit the building infrequently during his twenty-six years as Park Commissioner because he didn't want to be accessible to departmental employees--Moses was confronting the CWA. Its officials were worried themselves about the demoralization of the 68,000 relief workers in the parks. Moses told them that the first requirement for //(p. 369) getting those men working on worthwhile projects was to provide them with plans. Blueprints in volume were needed, he said, and they were needed

immediately. He must be allowed to hire the best architects and engineers available and he must be allowed to hire them fast. The CWA must forget about its policy of keeping expenditures for plans small to keep as much money as possible for salaries for men in the field. The agency must forget its policy that only unemployed men could be hired so that Moses could hire a good architect even if he was working as a ditch digger or was being kept on by his firm at partial salary. And the agency must drop its rule that no worker could be paid more than thirty dollars per week. The CWA refused: rules were rules, it said. I quit, Moses said. La Guardia hastily intervened. After seven days of haggling, the CWA surrendered. Moses was given permission to hire 600 architects and engineers without regard to present job status, and to pay them up to eighty dollars a week. So that he could hire them as fast as possible, he was even given an emergency allocation to summon them to interviews not by letter but by telegram.

"The CWA capitulated on the morning of January 27. By noon, 1,300 telegrams were being delivered to carefully selected architects and engineers all over New York State, telling each of them that if he was interested in a job, he should report to the Arsenal the next day.

"No profession had been hit harder than architecture and engineering. Engineers were particularly reluctant to accept relief. "I simply had to murder my pride," one said. "We'd lived on bread and water for three weeks before I could make myself do it." But The Nation estimated that fully half of all engineers were out of work--and six out of seven architects.

"These men had been hiding out in public libraries to avoid meeting anyone they knew, or tramping the streets carrying their customary attache cases although those cases contained only a sandwich. Although the Park Department interviews weren't supposed to begin on January 28 until 2 P. M., on that day, with the temperature below freezing, when dawn broke over the city, it disclosed a line of shivering men outside the Arsenal. The line began at the front door. It wound down the steps, out onto Fifth Avenue at Sixty-fourth Street, and along the avenue to Seventy-second Street.

"The interviewing went on all day; some of the men who had been waiting on line before dawn didn't get into the Arsenal until late afternoon. But for 600 of them the wait was worth it.

"`When you got inside, nobody asked you how much money you had in the bank or what was the maiden name of your great-grandmother,' one architect recalls.  `All they asked you was: `What are your qualifications?' Those whose qualifications satisfied Moses' men were hired on the spot, shown to the Arsenal's garage, in which drafting tables had been set up, handed assignments and told to get to work. In the evening, some started to go home. Those whose assignments didn't have to be finished for a few days were allowed to do so; several hundred whose plans were needed faster were told flatly, `If you go home tonight, don't come back tomorrow.' Without exception, these men stayed, catching naps on cots Moses had had set up in the Arsenal's corridors. //(p. 370)
"Out in the parks, the ragtag ranks of the CWA workers were being shaped up.

"Moses had found the men to do the shaping. Out of fear of losing them permanently to rivals, idle construction contractors were struggling to keep on salary their `field superintendents,' the foreman or `ramrods' whose special gift for whipping tough Irish laborers

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into line made them an almost irreplaceable (sic) asset. Pointing out that the CWA was not a rival and would probably go out of existence when business improved, Moses persuaded contractors throughout New York, New Jersey, Pennsylvania, and New England to give him their best ramrods, `the toughest you've got.'  And when the new men arrived, 300 in the first batch, 450 more within two months, his instructions to them were equally explicit.  CWA workers, he was to say later, `were not accustomed to work under people who drove them. I see to it that my men do drive them.'

(p. 374) "In Central Park, Moses' men restored Olmsted's long-defaced buildings, replanted the Shakespeare garden, placing next to every flower a quotation from the Bard in which it was mentioned, and exterminated herds of rats; 230,000 dead ones were counted in a single week at the zoo site alone. While seven hundred men were working night and day to build a new zoo, another thousand were transforming the dried-up reservoir bed that had been called `Hoover Valley'--Moses had torn down the shanty town there--into a verdant, thirty-acre `Great Lawn,' were laying flagstone walks around it and planting along them hundreds of Japanese cherry trees. Then, having satisfied those who objected to use of the reservoir bed entirely for active (sic) play, Moses constructed a playground and wading pool in the northeast corner of the bed, outside the lawn's borders, for small children and a game field in the northwest corner for older children. On the North Meadow he built handball courts, wading pools and thirteen baseball diamonds. He deported the deformed sheep and turned the old sheepfold into a `Tavern-on-the-Green,' and old English inn-in-a-park (sic) complete with doormen wearing riding boots and hunting coats and top hats and cigarette girls in court costumes complete with bustles--and with the added touch of an outdoor flagstone terrace on which couples could dance among tables shaded by gaily colored umbrellas to the music of a twelve-piece orchestra costumed in forest green.

(p.379) "The cheers of the press were echoed by the public. While the parks were blossoming with flowers, editorial pages were blossoming with letters from the public praising the man who had planted them. And it was not unusual at park (sic) and playground opening ceremonies for children, prodded by their parents, to break into the cheer `Two, four, six, eight--who do we appreciate? Mr. Moses! MR. MOSES!! MR. MOSES!!!' //(p. 380)

"The cheers rose to a crescendo when the Central Park Zoo reopened on December 3, 1934.

    "Moses had a personal reason for being interested in the zoo. Nineteen thirty-four had been a sad year for Al Smith. The public humiliation to which Jimmy Walker had subjected him at the Inner Circle dinner was only one indication of the fact that there was (sic) no longer any place for the old leader in the organization he had led and loved. Only sixty years old, as vigorous as ever, Smith wanted desperately to play a role (sic) in the federal government's efforts to end the human misery caused by the Depression. No man was better qualified; Roosevelt himself had told Frances Perkins, `Practically all the things we've done in the federal government are like things Al Smith did as Governor of New York.' Roosevelt had asked Smith to campaign for him against Hoover, and Smith had done so. And when Roosevelt had won, Smith had told acquaintances flatly that a man did not feud with the President of his country, he gave him loyalty. He only hoped, he said, that Roosevelt would allow him to work for him. But Roosevelt, another young man of whom Smith had been fond and whom he had helped up the

political ladder, refused even to consider him for any federal post. And if Smith considered this the ultimate humiliation, he learned during 1934 that it was not. Worse was to come. When John J. Raskob and the other businessmen who controlled the Empire State Building Corporation had offered him its presidency, they had told him the post was honorary, but, with the skyscraper completed, the Depression made it so difficult to obtain tenants that the corporation was on the verge of bankruptcy, and they told him he would have to do something to earn his $50,000 a year: he would have to go to Washington and beg Roosevelt to throw some government leases his way. For months, Smith refused, but he was finally persuaded that loyalty to his friends required him to help them. Roosevelt responded generously to his entreaty--federal agencies were moved out of offices as far away as Philadelphia to fill up the New York skyscraper--but now in the late afternoons, when Moses dropped by to see him, he would often find the man who had been called the Happy Warrior sitting staring out the windows of his apartment with new lines of bitterness and disillusionment hardening on his face.

"Moses knew how much the old Governor loved animals and he knew he missed the little zoo he had maintained behind the Executive Mansion in Albany. The former Governor and Katie now lived at 820 Fifth Avenue, almost directly across from the Menagerie, and Smith spent a lot of time strolling among the cages, feeding and talking to the animals. Saddened by the unsanitary conditions in which they had to live and the lack of care for their physical ailments, Smith was horrified when he learned that in case of fire the animals might be shot. When Moses was appointed Park Commissioner, Smith told him he would regard it as a special favor of the Menagerie were improved.

"Moses gave the job top priority. When materials and equipment ran low--because of the CWA's reluctance to spend money on them, they were //(p.381) always running low--what was available was diverted there from other projects. The best ramrods were put on the job to drive the thousand men working around the clock in the fenced-off area behind the Arsenal. Most of the animals had been moved out, but not all, and the lions, shunted from one animal house to another as the buildings were torn down and kept awake by the glow of the carbide flares and the pound of the pneumatic drills, roared through the night, while (sic) a reporter who visited the site early one morning found the Menagerie's old polar bearing pacing 'restlessly up and down in bewilderment, pausing occasionally to peer out at the grimy, torch-lit laborers.' The residents of Fifth Avenue apartment buildings near the site roared, too, but Moses refused even to listen to their complaints. Often, in the evenings, he would suddenly materialize on the scene, joking with the field superintendents and with the men, encouraging them, telling them how important their work was, urging them on. All summer and fall, he spurred the job with a special urgency. And when it was finished, on December 2, he turned the reopening into a surprise party for Al Smith.

"It was quite a party. Some observers said New York had never seen anything like it. To emphasize that he was trying to make the zoo not so much a great animal museum like its counterpart in the Bronx but a place of delight for young children, Moses had already dubbed it a `picture-book zoo,' and when the twelve hundred invited guests filed into the stands set up in front of the Arsenal for opening ceremonies--twenty-five thousand other persons lined Fifth Avenue waiting to be admitted--they found that in front of the zoo entrance had been erected a six-foot-high wooden replica of an open picture book, with painted green elephants charging

across its bright-yellow pages. Flanking the speakers' platform were two huge boxes wrapped in striped (sic) and polka-dotted paper and adorned with satin bows like a child's present. As the ceremonies began, four olive-clad trumpeters blew a flourish, the wrapping paper was pulled away--and inside one box was a cage containing a lion, inside the other a cage with a gorilla. Public Welfare Commissioner William Hodson, called to the microphone to give a speech, startled the audience by breaking instead into several choruses, delivered in a rather wheezy tenor, of `Oh, I went to the animal fair.' Thousands of balloons were released at intervals to fill the air with color until they were wafted northward by the prevailing breeze. Uniformed, flag-bearing high-school bands and elementary-school fife-and-drum corps came marching, one after the other, up Fifth Avenue. And clattering around the corner of the Arsenal came a team of white ponies drawing a tiny, gaily colored barouche in which sat a little girl holding a large gold key with which La Guardia could 'unlock' a door in the middle of the picture book and thus officially open the new zoo.

"But before La Guardia got the key, there was something for Smith. Moses had given the former Governor no hint that he would even participate in the ceremonies, simply telling him that there would be (sic) a seat for him on the reviewing stand. But when the old warrior walked out the front door of his apartment house to make his way to the stand, he found three hundred schoolchildren from the Fourth Ward lined up in front of the door, cheering //(p. 382) and waving balloons, waiting to escort him across Fifth Avenue. He found that his seat was in the place of honor next to La Guardia. (Moses, who had been supposed to sit on his other side, was absent; during the past week he had refused to take a day off despite a severe case of influenza, and doctors summoned over his protests by a worried Mary just two hours before the ceremony began found him in a state of complete collapse and ordered him to bed.) Hardly had Smith sat down when he realized that he was being summoned to the microphone himself, and Earle Andrews, substituting for Moses, pinned to his lapel a large, elaborately engraved medal with a lion's head on its face and announced that he was now, and permanently, `Honorary Night Superintendent of the Central Park Zoo.'  As Andrews finished speaking, a horse-drawn wagon, reminiscent of those Smith had chased through the Fourth Ward in his youth, rolled around the corner of the Arsenal, and it was jammed with boys--from the Fourth Ward--singing, `East Side, West Side.' The horses pulled up in front of him and eleven-year-old Eddie McKeon jumped out and presented him with a large Christmas turkey as the whole reviewing stand stood and joined in singing his old campaign song.

"The old Governor's eyes were tearing, from the cold December wind, no doubt, and it took some time for him to clear them, and even after he did he spent a rather long time chewing on his cigar, which was already in shreds, before he began to speak, but when he did, he knew exactly what he wanted to say. `When Mr. Moses was appointed Park Commissioner, I used all the influence I had with him to get him to work on a new zoo', he said, `And now look at him! In less than eight months, we've got a zoo that's one of the finest of its kind in the world.' Smith began then to recite the whole list of Moses' achievements, stopping only when he noticed the children on line trying to peer over the park wall at the cages. Cutting himself short, he said with a smile, `I bid you welcome to this new zoo as night superintendent, and I hope you have a good time,' and sat down.

"Later that week, when he was well enough to tell him himself, Moses informed Smith that the night superintendent carried with it certain privileges. He gave Smith a master key which unlocked the animal houses and told the Governor that the zoo caretakers had been instructed that he was to be allowed to enter them whenever he wanted, day or night. And until the end of his life, Smith would delight in this privilege. The doormen at No. 820 would become accustomed to seeing him walk out the front door in the evenings and cross Fifth Avenue under the street lights, a somewhat paunchy figure with a big brown derby set firmly on his head and a big cigar jutting out from his face, and disappear down the steps of the darkened zoo, not to reappear for hours. The former Governor and presidential candidate would walk through the animal houses, switching on the lights as he entered each one, to the surprise of its occupants, and talk softly to them. He would have in his pocket an apple for Rosie, the huge hippo. And if one of the zoo's less dangerous (sic) animals was (sic) sick or injured, Smith would enter its cage and stand for a while stroking its head and commiserating with it. When he had dinner guests, he would take them along and, since (sic) //(p. 383) they were usually Tammany stalwarts unhappy at what La Guardia was doing to the Tammany Tiger, they delighted in a little show he would put on with the zoo's biggest (sic) and fiercest tiger, who could be counted upon to respond angrily if anyone growled at him. When Smith and his guests approached, the tiger would be sitting silently staring at them through the bars. Smith would walk up to the cage, thrust his head toward the bars and, in his deepest and harshest voice, roar at the tiger, 'La Guardia!' The tiger would snarl, bare its teeth and leap at the bars, growling in what Smith's daughter describes as 'obvious disapproval.'

"While (sic) there were (sic) cheers aplenty for Smith at the zoo opening, however, there were (sic) plenty left over for Moses.

"The invited guests on the reviewing stand had been startled by the transformation in the Arsenal. The stucco had been sand-blasted (sic) off its walls, revealing handsome dark-red bricks. The cupolas had been torn off its turrets, revealing battlements complete with archer's slits. The newel posts of the banisters on the stairs leading up to its front entrance were now upturned Colonial cannon muzzles, and the banisters themselves were supported by wrought-iron imitations of Colonial flintlock rifles, painted white. Atop the gleaming white doorway, whose lintel had been crenulated to mirror the battlements on the roof above, an eagle glared from between two carved mounds of cannon balls, and on the jambs had been carved crossed swords and Indian spears. The large lamps on either side of the door had been enclosed in wrought-iron replicas of tasseled drums like those carried by Revolutionary War drummer boys. And above the doorway three large flags fluttered colorfully from flagpoles. All in all, the once shabby (sic) wreck looked quite like a little fort, a gay little fort that when seen in miniature from the higher floors of Fifth Avenue apartment houses seemed almost to have been set in the park by mistake and really to belong six blocks down the avenue in the windows of F. A. O. Schwarz.

"And when La Guardia `unlocked' the door in the bright-yellow picture book, after asking the Honorary Night Superintendent's permission, the crowd followed the two men through the door and through a short corridor erected for the occasion, its walls covered with picture-book inscriptions such as `A is for Ape,' `B is for Buffalo,' Emerging on the side of the Arsenal, they found there was (sic) nothing left of the old Menagerie at all. Where they had been accustomed to see ramshackle wooden animal houses, they found, to their astonishment, neat red

brick (sic) buildings decorated with murals and carved animal friezes, connected by graceful arcades that framed park vistas beyond--and framing a sea-lion pool set in a handsomely landscaped quadrangle.

"Moses had wanted to use distinctive materials as he had used Barbizon brick and Ohio sandstone at Jones Beach, but the CWA's refusal to purchase any but the cheapest materials had forced him to settle for concrete, plain red bricks, and some cheap limestone, and to forgo dozens of imaginative little touches he had planned.//(p. 384)

"But the eye of the visitor still found plenty to delight it. The sea-lion house in the pool was constructed of unadorned concrete, but it was constructed so that visitors could watch the sea lions even while they were inside. The paths to the pool divided a sunken landscaped quadrangle into four separate, neatly trimmed lawns. Each was surrounded by low hedges. In the center of each was a wonderfully gnarled and twisted Japanese ginkgo tree. The steps leading down to the quadrangle were flanked by fierce-visaged stone eagles big enough to glower eyeball to eyeball at many of the children walking past them. And in its four corners were huge Victorian flying cages from which glowered live eagles.

"On the far side of the quadrangle, at the animal-house level, past the cavorting sea lions, the stone eagles, the lawns, the shrubbery and ginkgo trees, the eye was startled by a large lioness proudly holding up for inspection a peacock she had killed, while her two cubs sniffed at the beautiful tail dangling limply to the ground--a bronze statue that had stood in some seldom visited (sic) corner of the park for seventy years until Moses rescued it. And behind the statue was a long, low terrace on which little tables topped with gay parasols sat in the shade of a bright, vertically striped awning eighty feet long--an outdoor dining terrace on which diners could sit and be entertained by the sea lions and by the crowds being entertained by the sea lions. And as the eye followed the vertical stripes of the awning upward, it abruptly found itself being stared back at by lions, tigers, elephants, and hippopotomi gathered under waving palm trees -- for the cafeteria's eighty-foot-long clerestory had been covered with a droll animal mural.

"Throughout, the zoo was proof piled on proof that Moses had been able, to some extent at least, to make imagination take the place of money.

"The CWA had insisted that the animal houses be constructed primarily of common red brick and concrete, but Embury, an architect accustomed to working with the costliest of materials, nevertheless succeeded, under Moses' prodding, in making them attractive. Their proportions were exceptionally well balanced, their lines exceptionally clean. Some of the brick had been used to place charming ornamental chimneys on their roofs. Some more had been used for designs that broke the monotony of the concrete clerestories. Connecting the animal houses with arcades gave the whole scene unity.

"And the zoo buildings were adorned with little touches that, as at Jones Beach, scaled down the architecture `to the size of a good time.' Tiny, delicate cast-iron birds perched atop the lamps that flanked the doors of the animal houses. Slender rods topped with little white balls held big white globes that cast light over the walk in front of the cafeteria terrace. The lamps

hanging in rows in the animal houses were glazed balls, but around each ball was a slanted copper ring that made the fixtures look like a long row of Saturns whirling in the sky.

"No one had to wonder what was in each building. Around the top of each wall was a frieze, carved in low relief in limestone panels, depicting its occupants in marvelously lifelike poses; among the figures over the monkey houses, for example, were a monkey chasing butterflies and a gorilla chewing a twig with a wonderfully contemplative expression upon his face. And//(p. 385) the weathervanes atop each building were comic depictions of one of the building's inhabitants, done by the unknown designers who had caused architects from all over the world to exclain at the weathervanes at Jones Beach; the one over the bird house, for example, showing a spindly-legged heron jutting its long bill under water in search of food, was a miniature masterpiece of angularity silhouetted against the sky.

"The purpose of a park, Moses had been telling his designers for years, wasn't to overawe or impress; it was to encourage the having of a good time. Wheeling through the park were movable refreshment carts. But these weren't ordinary refreshment carts. They were adorned with painted animals and garlands of flowers in colors that were intentionally gaudy--replicas of gay Sicilian carretinas. Their operators were dressed in costumes that were extravagantly Sicilian. Even their wares were special; in addition to the standard peanuts, sodas and candy bars, each carried, prominently displayed on top, whirling silver-foil windmills, strings of brightly colored balloons, flags, banners, braided whips--and stacks of animal picture (sic) and coloring (sic) books. And to blow up balloons, the zoo was equipped with the latest in balloon-blowing devices--the `Kelly's Rocket,' whose windy woosh delighted children. And the decision to build the zoo around a sea-lion pool was the crowning touch; the boisterous barking (sic) and slippery antics of these traditional circus clowns, the raucous enthusiasm with which they played tag under water, dove for the fish thrown to them by keepers and playfully slithered big-bellied (sic) and long-necked (sic) around their concrete home, insured that the central panorama would be one to delight any child--and any adult who had any child left in him. On a summer day, when the animals were all outside, and the central quadrangle in which the sea lions frolicked was lined with black-and-white-striped zebras, tan lions, furry brown monkeys and red-rumped baboons, the central panorama was, as near as any man could make it, given the CWA's stinginess, exactly what Robert Moses had envisioned--a scene out of a child's picture book.

"And the zoo was viewed as the triumph it was. Some zoophiles, ignoring the violet-ray baths Moses had installed so that monkeys would get their necessary quota of sun in winter, the specially designed scratching posts set up for the lions and the replacement of Tammany's rifle-toting keepers with trained animal experts and doctors (sic), criticized the concrete floors of the cages, which they said would give the animals tender feet. But architects, as quoted in Fortune, found the architecture `gay and amusing and occasionally pointedly absurd.'  Architectural Forum called the view from the cafeteria terrace `the finest eating view in the city.' The press cheered, too. And the public gave its own vote of confidence. The crowds that streamed into the zoo behind Laguardia and the Honorary Night Superintendent on opening day numbered 32,000, a figure that Moses found so unbelievable that he ordered the counters he had installed at the entrance double-checked (sic). But the next Sunday, after word of mouth about the new zoo had had a week to spread, attendance was 57,000. By 1935, on an average Sunday, more than 100,000 visitors would come to the picture book in the park."

History of Bedrock Geologic Investigations

The earliest written record on the geology of New York City comes from a report by Johann David Schopf, published in 1787, entitled "Beytrage zur mineralogischen Kenntniss des ostlichen Theils von Nord-Amerika und seiner Geburge" ("Contributions to the mineralogical knowledge of the eastern part of North America and its mountains"). Schopf's thorough report was translated and annotated by Edmund M. Spieker and published by the Hafner Publishing Company, New York in 1972 (now out of print). Schopf's comments are limited to the mineralogy, lithology, and topography of Manhattan and the New York City area (including Long Island) but his report did not include a geologic map. S. L. Mitchill (1798) wrote "A sketch of the mineralogical and geological history of the State of New York" but we were not able to obtain a copy at press time for this guidebook so we do not know about its contents. According to Speiker (1972), Schopf's observations did not serve as a foundation for Mitchill's apparently independent contribution.

Maclure's (1817) water-colored regional map of the eastern United States (Figure 3) adopted the rock-stratigraphic nomenclature of Abraham Gottlob Werner and the Neptunists (not a punk-rock band but an early "school of geology" that presumed that all rocks had formed in a "Universal Ocean"). Maclure, in fact, considered all of the metamorphic rocks of New England (and the entire Appalachian belt, for that matter) to represent Werner's "Primitive Series" of rocks. In the accompanying 127-page text, Maclure located the primitive rocks of the Hudson Highlands and those east of the Hudson River. He astutely discussed and correlated the metamorphosed dolostone- and limestone sequences cropping out as far distant as Stockbridge and Kent, Connecticut, Dover and in the Bronx, New York, with those found roughly three hundred miles away near Philadelphia, Pennsylvania. In the areas examined by Maclure, the extensive belt of carbonates is now known as the Sauk Sequence [Cambrian to mid-Ordovician; our Layer IIA(W) in Table 2 (=most of the Inwood Marble and correlatives).
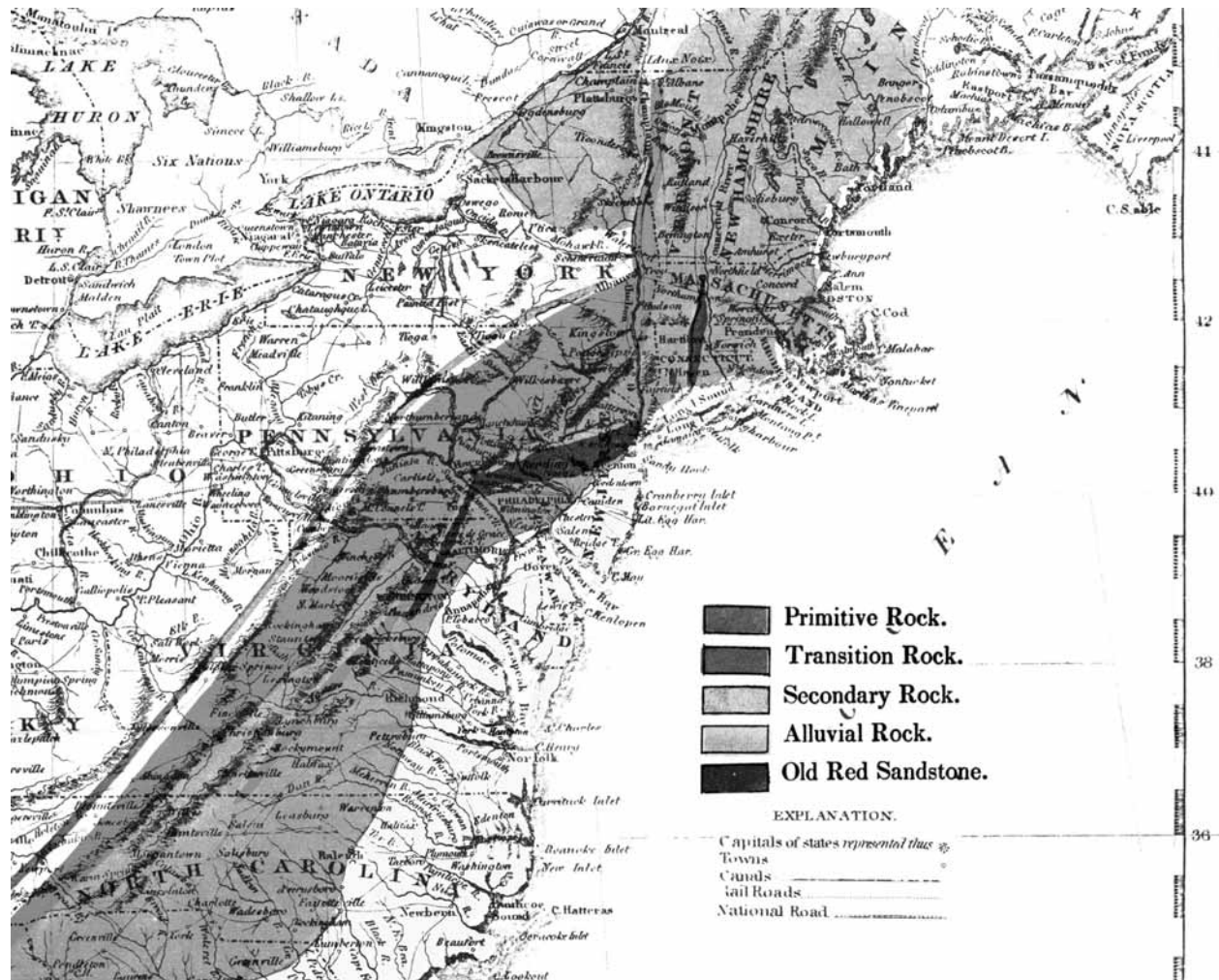
Figure 3 - Northeastern part of William Maclure's geologic map of the United States (1817).

James Pierce (1820) described the regional geology and mineralogy of New York and New Jersey but concentrated on the scenery and mineral deposits of the trap-rock areas of New Jersey. He mentioned the rocks of the Hudson Highlands and described New York harbor but did not discuss the geology of New York City. L. D. Gale's contributions [1839, and in an addenda in Mather (1843)], together provide a thorough account of the glacial- and bedrock geology of Manhattan in the format of a street-by-street diary before many buildings had been constructed. Thus, Gale's diary, provided the first detailed report on the structure- and lithology of Manhattan Island (without a map, unfortunately), discussed the glacial boulders found in situ, and included drill-core data and construction costs. Gale's (1839) observations (with field work conducted in 1828-1829) on glacial features are included in a later section.

In his study of the First Geological District under the auspices of the Geological Survey of New York, Mather (1843) produced the first geologic map of the New York City area. Drawing heavily from Gale's investigations, Mather's map of New York included the five boroughs (Figure 4) and showed the distribution of "Primitive" crystalline rock including granite, gneiss (uncolored in Figure 4), "limestone of New York County" (black lenticular areas

in Figure 4), serpentine (on Staten Island), and overlying alluvial sand and marshland, and drainages. In these halcyon days of geologic mapping, all crystalline rocks were lumped together as the Primitive Series (Proterozoic and Archean of the modern usage). Note the marble quarry in the area of the Bronx extending up from West Farms on Figure 4 and the stream flowing southward to the west of and parallel to the Bronx River (in the Webster Avenue valley). This former stream valley has now been totally filled in; the New York Central railway (now Metro-North) occupies most of its strike length.

Figure 4 - Portion of Mather's (1843) map of New York City and vicinity that accompanied his report on the First Geological District of the State of New York. Notice that the built-up area of Manhattan is confined to the southwestern part of the island.

A north-south geologic section of Manhattan or New York Island accompanied a 114-page report by Issachar Cozzens in 1848. Reproduced in Figure 5, Cozzens' section shows a continuous granite substrate overlain by gneiss, limestone, amphibolite, serpentine, and glacial "diluvium". For an excellent review of American geology from the late eighteenth to late nineteenth centuries, the interested reader is urged to consult George P. Merrill's book on the history of geology (1924).
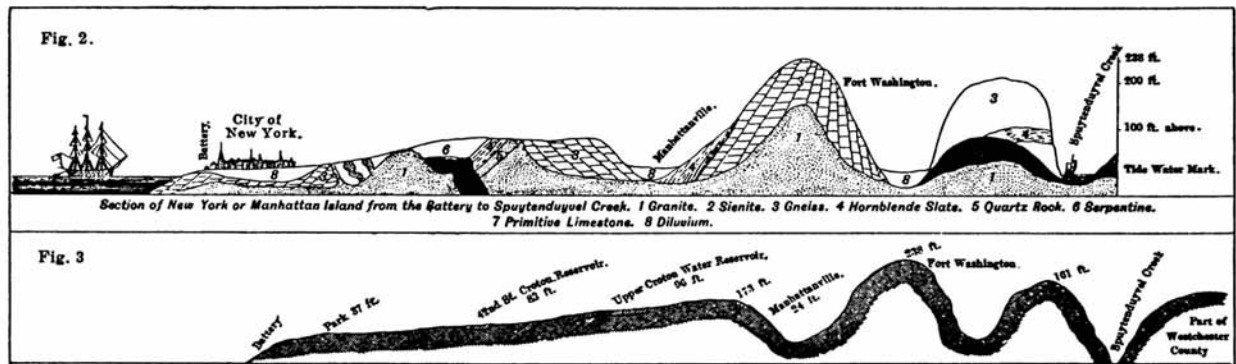
Figure 5 - N-S profile of Manhattan, from Battery (L) to Spuyten Duyvel Creek (R), showing shape of land surface (shaded, below) and inferred geological relationships as determined by Issachar Cozzens (above; G. P. Merrill, 1924, fig. 43, p. 238, from Cozzens, 1848, reference not in our bibliography).

Before the turn of the century, many geologists were examining the geology of New York City as building construction and industrial development began in ernest. Reports based on work by Frederick J. H. Merrill (1886a, b; 1890, 1891a, b; 1898a, b, and c) on the glacial- and metamorphic geology of New York City, examination of metamorphic rocks in Dutchess County by J. D. Dana (1880, 1881, 1884) and the Harrison granodiorite gneiss in adjacent Westchester County by Heinrich Ries (1895), and J. F. Kemp's studies (1887, 1895, 1897), provided important contributions to our knowledge of both the glacial- and bedrock geology of southeastern New York. The first detailed geologic map and structure sections across Manhattan Island and sections across the East River at Seventieth Street were published before the close of the nineteenth century (Kemp, 1887, 1895; reproduced here as Figure 6).

In 1890 (p. 390), Merrill named the Manhattan Schists for the micaceous metamorphic rocks found on Manhattan Island and suggested, following the views of Professors W. W. Mather (1843) and J. D. Dana (1880), that they represent metamorphosed equivalents of the Paleozoic strata of southern Dutchess County, New York. An obscure reference in Merrill (1890) states that "the name Manhattan Group was proposed by R. P. Stevens, Esq., to include the rocks of New York Island". Merrill extended "Group" status to include the Manhattan Schists, the Inwood limestone, Fordham Gneiss, and the Yonkers Gneiss. Later, in 1902, Merrill and coworkers correctly correlated the Fordham gneiss with Precambrian sequences of the Hudson Highlands. Formal removal of the significantly older Fordham and Yonkers gneisses from the "Manhattan Group" had to await the refinement and application of radiometric-dating techniques and detailed mapping of lithologies in the 1960's. Formal "de-Grouping" of the "Manhattan Group" took place after spirited debate at a Symposium on the New York City Group of Formations at the 1968 meeting of the New York State Geological Association at Queens College, Queens, New York.

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Figure 6 - Geological map and profile-sections drawn parallel to streets, Manhattan, with subsurface relationships in southwestern part based on borings. Notice that the scale of the profile-sections does not match that of the map. (J. F. Kemp, 1887.)

Merrill, in concert with other geologists, published the first comprehensive geologic map of New York City in the United States Geological Survey New York City Folio (1902). In this compilation, based on previous studies, Merrill outlined, in map form (Figure 7) the basic stratigraphic- and structural framework that modern geologists would test, promote, and amplify upon. Merrill's major contribution was subdivision of Mather's Primitive Series into mappable units. He first defined the correct relative chronology of the basal Precambrian Fordham Gneiss ([fgn] = white stippled pattern in Figure 7), the overlying Cambrian to Silurian? Stockbridge dolomite ([CSs] = light-colored areas with horizontal ruling in Figure 7), and the Silurian Hudson Schist ([Sh] = dark shaded areas in Figure 7 now known as the Manhattan Schist and correlatives). In keeping with the stratigraphy proposed by Dana for Dutchess County, Merrill and coworkers chose to use the name Hudson Schist for the schistose rocks of New York City and considered them to be of Silurian age. Thus, they served up a layer-cake model (non-iced and without coffee), gave the general age assignments (the modern reader should substitute Ordovician for Silurian above), and made the regional lithostratigraphic correlation between the metamorphic rocks of New York City and those of southeastern New York. The pioneering work by Merrill and coworkers set the stage for a series of detailed investigations in the early 1900's by many geologists that helped define the lithology- and structure of New York City bedrock units. On the basis of this knowledge, massive engineering construction projects including power generation, water supply, transportation, and sewage disposal were able to proceed, literally on a firm footing.

Before 1945, workers such as Hobbs (1905a, b), Kemp (1907, 1909, and 1910), Gratacap (1909), Ziegler (1911), Berkey (1907, 1910, 1911, 1930, 1933), Berkey and Healy (1911), Flinn (1913), Fettke (1914), and Reeds (1925, 1926, 1927, 1930, 1933), helped form our modern views on the bedrock geology of New York City and vicinity. In 1933, Berkey directed preparation of a guidebook for field trips in New York City held in connection with the 16th International Geological Congress meeting in Washington, D. C., which included summary sections by A. K. Lobeck on the Geography of New York City, the Geology of New York City by G. I. Finlay, the Pleistocene geology of New York City by C. A. Reeds, and a detailed section on the engineering geology of New York City by C. P. Berkey (basically a recap of his classic 1911 New York State Museum Bulletin publication on the geology of the New York City aqueduct).

Berkey (1933 field-trip guidebook) published a geologic map (Figure 8) showing a departure from Merrill's time-stratigraphic interpretation of bedrock units in the New York City area. Note that Berkey's map, (see legend, Figure 8) has "pushed back the temporal frontier" of Merrill's metamorphosed Paleozoic strata into the abyss of Precambrian time. Although Berkey adhered to Mather's "Primitive" stratigraphy, strangely enough, his map is based largely on the formational contacts published by Merrill et al (1902; New York City Folio). (Compare Figures 7 and 8.)

In the post-International Geological Congress period, Berkey, in his position as Chief Geological Consultant for the Board of Water Supply for the City of New York and his assistant Thomas W. Fluhr, were responsible for compiling engineering-drill-core data and tunnel maps which enabled them to enjoy a long-lasting tenure as the "experts" on New York City geology. This tenure resulted in a number of scientific publications on the geology of New York City including Murphy and Fluhr (1944), Berkey (1948), Berkey and Fluhr (1948), and a great

number of internal engineering reports by Berkey, Fluhr, W. O. Crosby and H. R. Blank which are listed and described in an important geotechnical summary by Fluhr and Terenzio (1984).

The multitude of engineering reports, maps, and boring logs by private-, state-, and municipal agencies provides a wealth of information on the geology of New York City. These documents can be divided into two groups: (1) those that were made in connection with projects carried out prior to the 1933 International Geological Congress (and also pre-Robert Moses) and (2) those related to projects that came after the 1933 Congress. In the first group are most of the tunnels for water supply, for the subways, and for the railroads; the older bridges across the East River; and the George Washington Bridge over the Hudson River. In the second group are mostly the parkways and interstate highways and the newer bridges (exception, Brooklyn-Battery Tunnel), including the Triborough Bridge, Bronx-Whitestone Bridge, Throggs Neck Bridge, and Verrazano-Narrows Bridge. J. J. Murphy, the engineer who was appointed to design the West Side Highway, started the vast project known as the "rock data map" of Manhattan. Murphy began by assembling all the data from the thousands of borings available to him in the mid-1930's. The project eventually involved a staff of geologists supported by the Works Progress Administration (WPA) using office space made available at Columbia University via Professor Berkey. Each boring log was drawn in ink on tracing linen; these are still preserved in the subsurface branch of the New York City topographic division. The data were compiled on a large-scale map of Manhattan showing the altitude of the bedrock surface (Murphy, 1940; Murphy and Fluhr, 1944). We have benefited from and therefore list the efforts of Singstad (1944), Berkey (1948), Berkey and Fluhr (1948), deLaguna (1948), deLaguna and Brashears (1948), Suter, deLaguna and Perlmutter (1949), Perlmutter and Arnow (1953), Blank (1934, 1972, 1973), Fluhr (1957), and Binder (1975, 1978) and a host of others which can be tracked down at the Engineering Society Library near First Avenue and 46th Street in New York City. At present, all the boring logs and engineering data on municipal contruction projects in New York City are archived at the New York City Subsurface Exploration Section, 1 Centre Street, New York, New York. Many of the cores from city construction projects are now at Hofstra University.

Figure 7 - Portion of Merrill et al's (1902) map showing the geology of the Bronx, parts of Manhattan, New Jersey, and Queens.

The geologic work of the 1950's and 1960's included detailed mapping in the vicinity of New York City by Norton and Geise (1957) on the Lowerre Quartzite and by Langer and Bowes (1969) and Bowes and Langer (1969) on the polyphase deformation of the Manhattan Schist in Manhattan and the Bronx. Broader-scale investigations in Westchester County and adjacent areas included attempts at regional correlation of the New York City "Group" by Balk and Barth (1948), Lowe (1949, 1950, 1958, 1959), Paige (1956), Prucha (1956, 1959), Scotford (1956), Prucha, Scotford, and Sneider (1968), Lowe and Schaffel (1958), Schaffel (1958), Hall (1968a, b, c; 1969), Seyfert and Leveson (1968, 1969), and by Ratcliffe and Knowles (1969). Early, typically inaccurate attempts at radiometric dating of metamorphism and cross-cutting igneous rocks by Long and Kulp (1958, 1962), Long, Cobb, and Kulp (1959), Clark and Kulp (1968), and Long (1961, 1969a, b) helped provide important "ballpark" estimates on the ages of metamorphism of the New York City strata and intrusion of crosscutting igneous rocks.
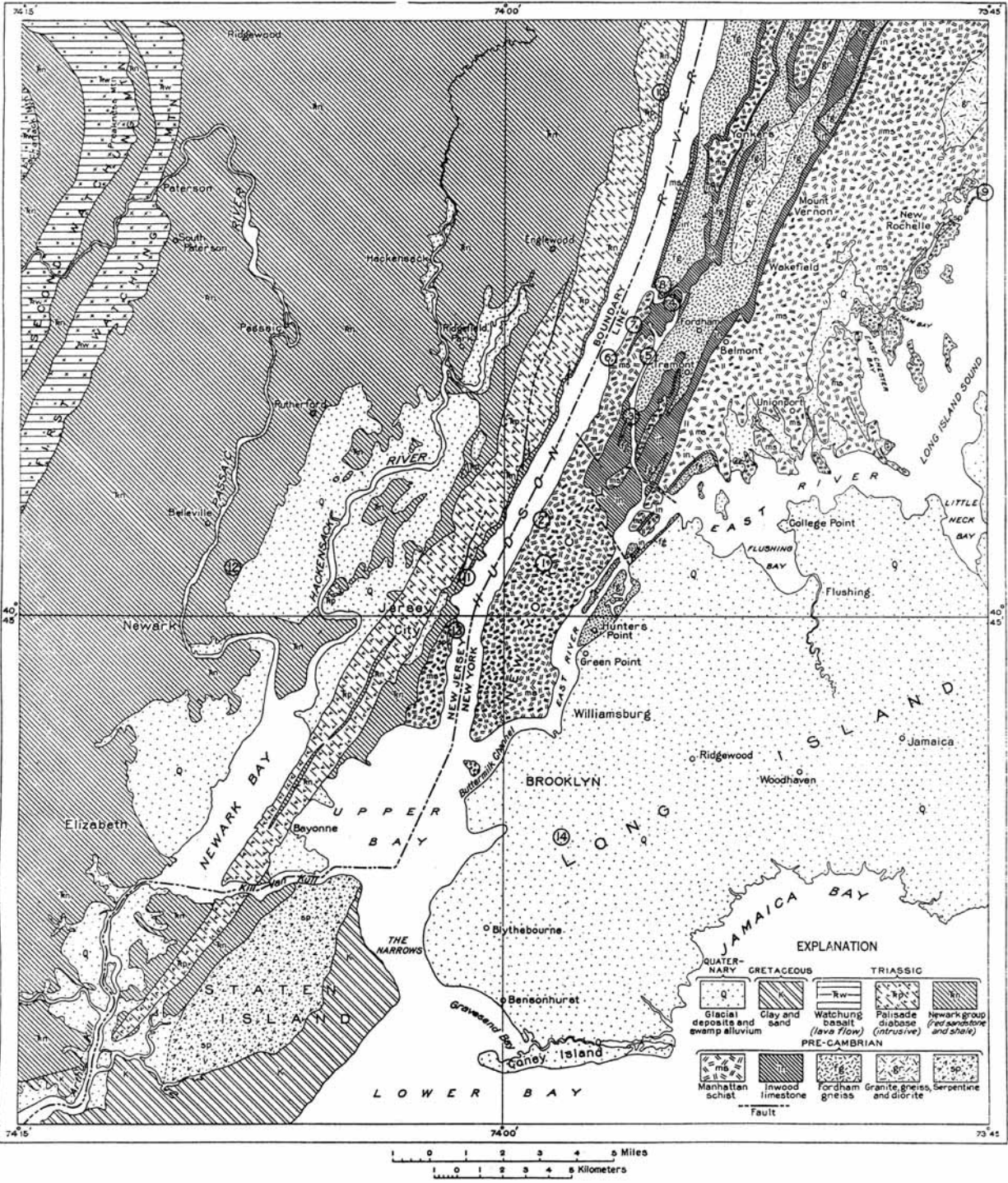
Figure 8 - Geologic map of New York City and adjacent part of New Jersey, generalized from U. S. Geological Survey Folio No. 83 (New York City, 1902). Circled numbers refer to trip stops on excursions offered by the 16th International Geological Congress, which met in the USA in 1933. (Berkey, 1933.)

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Most of the post-1945 work was summarized in four collegiate symposia on the geology of New York City held in 1958, 1968, 1985, and in 1986. The first of these, chaired by our dear friend, Professor Kurt E. Lowe (Professor Emeritus, The City College of New York, Ret.), was held at the New York Academy of Sciences in Manhattan. Lowe (1959) edited a series of papers (including one by himself on the Palisades Sill) presented at the conference into an annals volume published by the Academy which included papers on the geology of New York City by (Long, Cobb, and Kulp, 1959; Norton, 1959; and Prucha, 1959).

As mentioned earlier, a 1968 Symposium on the New York City Group of Formations, was held at a meeting of the New York State Geological Association at Queens College, Queens, New York. Based largely on the work of Paige (1956), Hall (1968a, b, c), Ratcliffe (1968), and Ratcliffe and Knowles (1968), the New York City Group of Formations was "de-Grouped." Leo M. Hall's demonstration that subunits of the Fordham Gneiss were truncated beneath various members of the Inwood Marble in Westchester County, provided the first, concrete evidence for an unconformity between the Precambrian rocks of the Fordham and overlying Paleozoic rocks of the Lowerre-Inwood-Manhattan sequence in the Manhattan Prong (Figures 9, 10). The combination of isotopic data and paleontologic evidence proved the Early Paleozoic age of the Inwood Marble. Based on superposition, the Manhattan Schist was considered younger than the Inwood but pre-Silurian based on regional relationships and the Late Ordovician age of the Taconic unconformity. Thus, by the late 1960's, a refined, layer-cake model (this time with icing but still, no coffee!) for the Lower Paleozoic strata was proposed which was basically in keeping with Merrill's original ideas.

Based on his work in the Glenville area of Westchester County, Hall (1968a, b, c; 1976, 1980), proposed subdivisions of the Manhattan Schist into lithically variable members (designated by letters A, B, and C). He correlated parts of the Manhattan Schist with Cambrian rocks of the Taconic allochthon of eastern New York State. Recent studies by Baskerville (1982a, b; 1987; 1989), Merguerian (1983a, 1986a, b), Mose and Merguerian (1985), Merguerian and Baskerville (1987), Taterka (1987), and Baskerville and Mose (1989), have demonstrated the extreme stratigraphic- and structural complexity of the Manhattan Prong in New York City. Not surprisingly, rather significant differences of interpretation of the stratigraphic- and structural relationships exist among the authors of these studies.

Starting in 1979, Merguerian (CM) began field- and laboratory investigations of the bedrock geology in the New York City area. CM's work drew heavily from earlier- as well as contemporary investigators. CM has concluded that the rocks assigned to the Manhattan Schist, as exposed in Manhattan and the Bronx, constitute a lithically variable complex consisting of three, mappable, roughly coeval, structurally complex, tectonostratigraphic units. Merguerian's investigations agree, in part, with designations proposed by Hall (1976, 1980), but indicate the presence of a hitherto-not-recognized-, structurally higher schistose unit that is a direct lithostratigraphic correlative of the Hartland Formation of western Connecticut (Merguerian, 1981, 1983b, 1984). CM's interpretations on the stratigraphy of the Manhattan Schist were presented during a lecture at the New York Academy of Sciences on December 17, 1984 entitled "Will the real Manhattan Schist please stand up!".
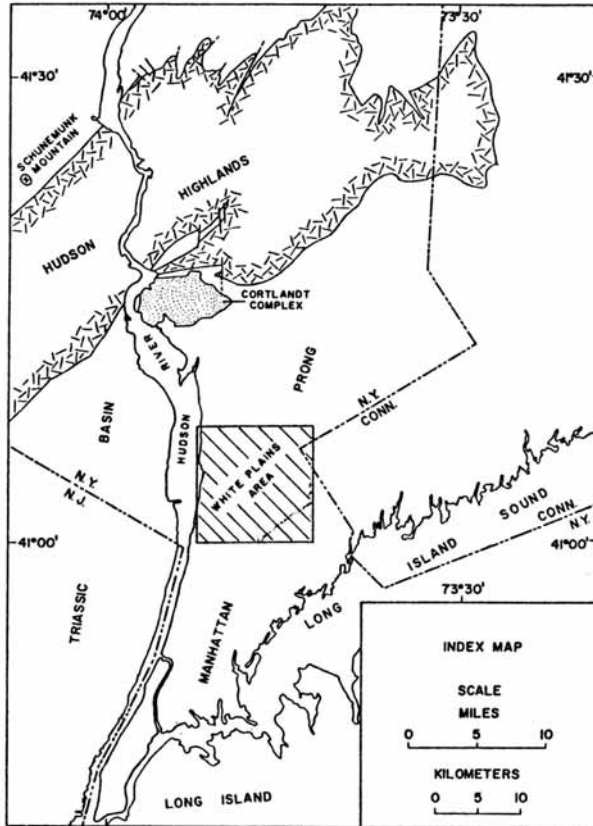
Index map for the White Plains area.
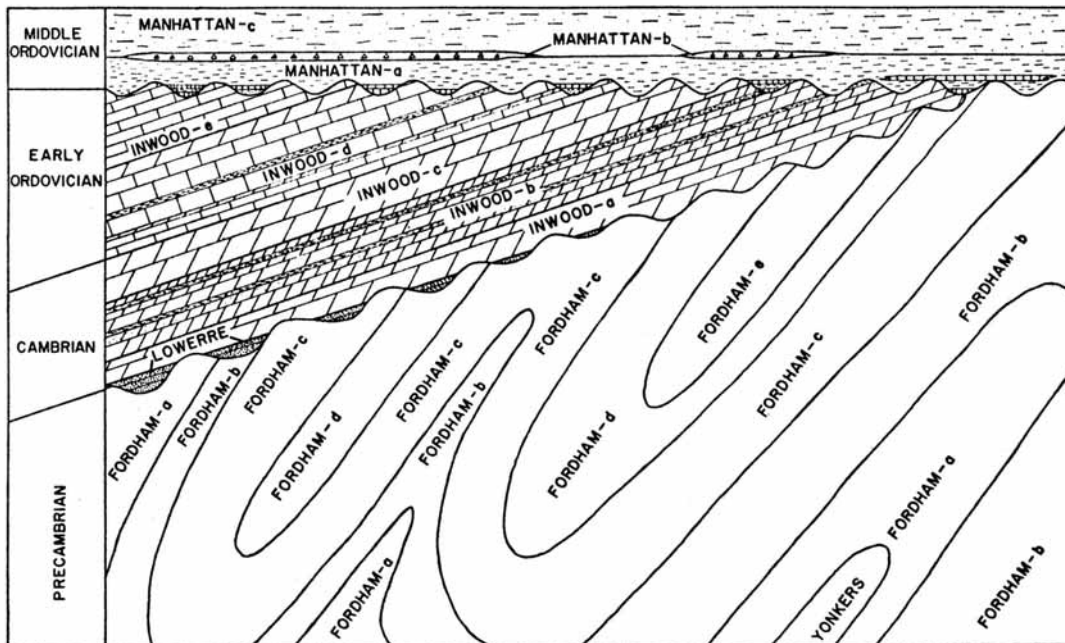

Figure 9 - Index map showing location of White Plains area (diagonal lines) and schematic profile-section showing inferred relationships among members of the Fordham Gneiss, Inwood Marble, and Manhattan Formation. (Leo Hall, 1968.)

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STRATIGRAPHY OF THE GLENVILLE AREA

AGE	FORMATION	MEMBER	BRIEF DESCRIPTION	REGIONAL CORRELATION
UNCERTAIN	HARRISON GNEISS		DARK GRAY BIOTITE AND/OR HORNBLENDE-QUARTZ-FELDSPAR GNEISS WITH SUBORDINATE QUARTZ.	UNCERTAIN. HAWLEY FORMATION (CHIDESTER AND OTHERS, 1967)
UNCERTAIN	HARTLAND FORMATION	S	BROWN OR BROWNISH-TAN WEATHERING GARNET-MUSCOVITE-BIOTITE-QUARTZ-FELDSPAR SCHIST AND MUSCOVITE-BIOTITE-QUARTZ-FELDSPAR GNEISS AND GRANULITE. THE SCHIST COMMONLY CONTAINS SILLIMANITE AND/OR KYANITE.	UNCERTAIN. MORETOWN FORMATION (CHIDESTER AND OTHERS, 1967)
		W	LIGHT GRAY OR WHITE BIOTITE-MUSCOVITE GNEISS WITH LOCAL GARNET	UNCERTAIN
		CP	INTERBEDDED GRAY OR WHITE BIOTITE-MUSCOVITE-GNEISS, BROWN OR RUSTY WEATHERING GARNET-MUSCOVITE-BIOTITE SCHIST WITH LOCAL SILLIMANITE AND/OR KYANITE AND AMPHIBOLITE.	UNCERTAIN — ROME SCHIST (CHIDESTER AND OTHERS, 1967).
		A	AMPHIBOLITE	UNCERTAIN
UNCERTAIN	MANHATTAN SCHIST	C	PREDOMINANTLY BROWN-WEATHERING FELDSPATHIC SILLIMANITE-GARNET-MUSCOVITE-BIOTITE SCHIST OR SCHISTOSE GNEISS; SILLIMANITE NODULES COMMON. ALTHOUGH SILICEOUS BEDS ARE PROMINENT IN SOME PLACES, BEDDING IS NOT COMMONLY CLEARLY DEFINED.	CORRELATION OF MEMBERS B AND C IS UNCERTAIN BUT THEY MAY BE EQUIVALENT TO THE WARAMAUG FORMATION (GATES AND BRADLEY, 1952), THE HOOSAC FORMATION (CHIDESTER AND OTHERS, 1967), AND LOWER CAMBRIAN AND CAMBRIAN (?) ROCKS OF THE TACONIC SEQUENCE (ZEN, 1967, FIG. 4).
		B	A DISCONTINUOUS UNIT OF AMPHIBOLITE AND MINOR SCHIST; ALTHOUGH THIS UNIT IS COMMONLY AT THE BASE OF MEMBER C, THERE ARE MANY PLACES WHERE IT IS WITHIN MEMBER C.	
MIDDLE ORDOVICIAN		A	GRAY OR DARK GRAY FISSILE SILLIMANITE-GARNET-MUSCOVITE-BIOTITE SCHIST WITH INTERBEDDED CALCITE MARBLE LOCALLY AT THE BASE.	BALMVILLE (FISHER, 1962) AND WALLOOMSAC (ZEN AND HARTSHORN, 1966).

~~~~~~~~~~ UNCONFORMITY ~~~~~~~~~~

AGE	FORMATION	MEMBER	BRIEF DESCRIPTION	REGIONAL CORRELATION
LOWER ORDOVICIAN	MARBLE	E	GRAY OR WHITE CALCITE MARBLE, COMMONLY TAN WEATHERING	COPAKE LIMESTONE AND ROCHDALE LIMESTONE (KNOPF, 1962).
		D	INTERBEDDED DOLOMITE MARBLE, CALCITE MARBLE AND SOME CALC-SCHIST.	ROCHDALE LIMESTONE AND HALCYON LAKE FORMATION (KNOPF, 1962).
CAMBRIAN	INWOOD	C	WHITE OR BLUE-GRAY CLEAN DOLOMITE MARBLE.	BRIARCLIFF DOLOMITE (KNOPF, 1962).
		B	INTERBEDDED WHITE, GRAY, BUFF, OR PINKISH DOLOMITE MARBLE, TAN AND REDDISH BROWN CALC-SCHIST, PURPLISH-BROWN OR TAN SILICEOUS CALC-SCHIST AND GRANULITES, TAN QUARTZITE, AND CALCITE-DOLOMITE MARBLE; BEDDING ONE HALF INCH TO FOUR FEET THICK IS PRONOUNCED.	PINE PLAINS FORMATION (KNOPF, 1962).
		A	WELL BEDDED WHITE, GRAY, OR BLUE-GRAY DOLOMITE MARBLE.	STISSING DOLOMITE (KNOPF, 1962).
	LOWERRE QUARTZITE		TAN OR BUFF-WEATHERING FELDSPATHIC QUARTZITE AND GRANULITE, MICACEOUS QUARTZITE AND GLASSY QUARTZITE; DARK GRAY, BROWN-ISH AND LOCALLY RUSTY-WEATHERING GRANULITE AND SCHIST THAT COMMONLY CONTAIN SILLIMANITE ARE LOCALLY PRESENT AT THE BASE.	POUGHQUAG QUARTZITE (KNOPF, 1962).

~~~~~~~~~~ UNCONFORMITY ~~~~~~~~~~

AGE	FORMATION	MEMBER	BRIEF DESCRIPTION	REGIONAL CORRELATION
PRECAMBRIAN	GNEISS	G	INTERBEDDED GRAY GARNET-BIOTITE GNEISS, GRAY BIOTITE-HORNBLENDE GNEISS AND AMPHIBOLITE.	UNKNOWN.
		AMP	PREDOMINANTLY AMPHIBOLITE WITH SOME GRAY BIOTITE-QUARTZ-FELDSPAR GNEISS.	UNKNOWN.
	FORDHAM	CS	LIGHT-GRAY, BROWN, WHITE, OR GREENISH CALC-SILICATE ROCK.	UNKNOWN.
		AM	AMPHIBOLITE.	UNKNOWN.
		P	PINKISH BIOTITE-QUARTZ-FELDSPAR GNEISS.	UNKNOWN.

Figure 10 - Correlation chart of the metamorphic rocks of southeastern New York (Hall, 1968a, b, c).

In 1985, a symposium in honor of Kurt E. Lowe, was held in conjunction with a meeting of the Northeast Section of the Geological Society of America, in Kiamesha Lake, New York and CM presented a paper on the geology of the East River. In 1986, Merguerian organized a conference on the Geology of Southern New York at Hofstra University, in Hempstead, New York, wherein both JES and CM spoke on glacial- and bedrock geology, respectively. Details on the metamorphic stratigraphy are outlined in a later section entitled - The bedrock stratigraphy of New York City.

With the development of plate-tectonic concepts to explain mountain building as the result of ancient plate interactions at lithospheric plate boundaries, new interpretations and models have been spawned by remapping orogenic belts such as the New England Appalachians (Merguerian, 1979; Hall, 1980; Robinson and Hall, 1980). In CM's view, the three ductile-fault-bounded Lower Paleozoic rocks (the three schist units of Manhattan), were juxtaposed during Medial Ordovician suturing of the eastern continental margin of North America and an offshore volcanic archipeligo (herein called the Taconic arc).

As mentioned in a previous paragraph, the three tectonostratigraphic units within the old Manhattan Schist are separated by two overthrusts. The "basal Taconic thrust," which elsewhere brings greenish continental-rise Taconic rocks above the black Tippecanoe rocks of the foreland-basin fill, is probably represented locally by what CM has named the St. Nicholas thrust. Higher up, Cameron's Line, is the overthrust contact between the continental-rise-type Taconic rocks and the oceanic-type Taconic rocks.

GEOLOGIC BACKGROUND

In this section, we summarize the bedrock units and features of Pleistocene age. Refer to Tables 1, 2, and 3.

BEDROCK UNITS

Under this section we describe some details of the geology of Layers I (Precambrian "basement") and IIA and IIB (Cambro-Ordovician strata). Under the second heading, we include some specifics about the bedrock stratigraphy of New York City, a primer on geologic structure, the structural geology of New York City (including the geology of Cameron's Line, geology of Central Park, faults and seismicity), the Taconic problem in New York City, and plate-tectonic interpretation.

Layer I: "Basement Complex" (Proterozoic Z and Y)

Precambrian rocks are now subdivided, by decree of the United States Geological Survey, into the older Archean (4.5 - 2.5 Ga [Ga = giga-, or billion years ago]) and younger Proterozoic (2.5 Ga - 575 Ma [Ma = million years ago]). Both Archean greenstone-gneiss terranes and crosscutting rocks of the Proterozoic mobile belts crop out to form the surface mosaic of the deeply eroded, 2.8 to 1.0 Ga, Canadian Shield of North America. The shield areas

(or cratons) contain the oldest rocks on Earth and form the essential "continental seed crystals", which eventually, through the effects of plate tectonics, collected fringing Phanerozoic mobile belts. In this way, the continents have grown radially outward through time, enabling them to push back the oceans and eventually, to cover 29% of the Earth's surface. Thus, the eroded remnants of past mountain-building episodes are preserved as the cratonic nucleii of our modern continents. North America is no exception.

The Canadian Shield consists of deformed metamorphic-, metaigneous-, and igneous rocks. The surface eroded across these formations dips southward. Thus, the basement rocks of the shield become buried beneath the Paleozoic- and younger strata of the central United States. These basement rocks do crop out on the surface in local areas associated with upwarps, fault blocks, and in elongate tracts along the core zones of both the Cordilleran and Appalachian mountain belts. The extent of crystalline basement rock in the vicinity of New York State is shown in a depth-to-basement map (Figure 11). This is essentially a negative contour map, produced by geophysical studies, that shows contours on the plunging surface at the top of crystalline "basement". Isachsen's (1964) map shows that the surface eroded on the top of the crystalline rocks trends east-west through most of New York State. This surface dips south- to southeastward from the Canadian Shield beneath the Appalachian Basin (marked as the Allegheny Synclinorium). The ancient North American craton is phenomenally exposed in the Adirondack Mountains and along fault-bounded basement massifs to the east and southeast (Green Mountains of Vermont, Berkshire Mountains of Massachusetts and northern Connecticut, and the Housatonic Mountains in Connecticut and New York. Grenvillian Proterozoic rocks are also exposed along the Hudson Highland-Reading Prong and in the adjacent Manhattan Prong. The Grenville rocks are also present in isolated areas such as Snake Hill (Berkey, 1933), Stissing Mountain (Knopf, 1962), and the Ghent block (Ratcliffe, Bird, and Bahrami, 1975). JES and CM suppport Isachsen's (1964) interpretation and suspect that many of these are remnants of ancient overthrust sheets. Some are of Taconian age; others, of the terminal-stage, latest Paleozoic Appalachian overthrusting. possibly all have been subjected to mid-Jurassic deformation that included strike-slip couples (Sanders, 1962; Merguerian and Sanders, 1991, 1993b).

The oldest recognized strata in southeastern New York include the Fordham Gneiss in the Manhattan Prong of Westchester County and the New York City area and the Hudson Highlands gneisses (Figure 12). The Highlands gneisses are composed of complexly deformed layered feldspathic gneiss, schist, amphibolite, calc-silicate rocks, and massive granitoid gneiss of uncertain stratigraphic relationships which together form an impressive, glacially sculpted cratonic sequence. Southeast of the Hudson Highlands, the Fordham has been intricately folded with Paleozoic rocks of the Manhattan Prong. We will not see any Fordham Gneiss today.

In the Pound Ridge area (PR in Figure 12), the Proterozoic Y gneisses of the Fordham have yielded 1.1 Ga Pb207/Pb206 zircon ages (Grauert and Hall, 1973) that fall well within the range of the Grenville orogeny. Rb/Sr data of Mose (1982) suggests that metasedimentary- and metavolcanic protoliths of the Fordham are 1.35 Ga. Farther south in Westchester County, subunits in the Fordham are cut by Proterozoic Z granitic gneiss (the Pound Ridge Gneiss and correlative Yonkers Gneiss [Y in Figure 12]. All Proterozoic units are unconformably overlain by the Lower Cambrian Lowerre quartzite (Hall, 1976; Brock, 1989). Using Rb-Sr, Mose and

Hayes (1975), have dated the Pound Ridge Gneiss as latest Proterozoic (579+21 Ma). This gneiss body shows an intrusive, or possibly an unconformable relationship (Patrick Brock, personal communication) with the Grenvillian basement sequence. The Yonkers Granitic Gneiss has yielded ages of 563+30 Ma (Long, 1969b) and 530+43 Ma (Mose, 1981). The Pound Ridge along with the Yonkers Gneiss, are thought to be the products of latest Proterozoic alkali-calcic plutonism (Yonkers) and/or
-volcanism (Pound Ridge?) in response to rifting of the ancient Gondwanan supercontinent.

Recent work by Pamela Brock (1989, and personal communication) in the vicinity of the Peach Lake quadrangle, New York and Connecticut, shows the presence of a vast rift sequence (now metamorphosed) of potash feldspar-rich felsic gneiss, calc-silicate rock, volcaniclastic rock, amphibolite gneiss, and minor quartzite (Ned Mountain Formation) that rest unconformably on the Fordham basement rocks. As such, Brock may have identified a metamorphosed, easterly volcaniclastic facies of Proterozoic Z intrusive igneous activity whose probable feeder area is now marked by the Yonkers and Pound Ridge gneisses. Together, the Proterozoic Y and Z terranes represent the ancient continental crust of proto-North America that was involved in both the Grenville orogeny and post-Grenville, pre-Iapetus extensional tectonic activity. Keep in mind that during subsequent Paleozoic orogenesis, these ancient rocks were involved in intense compressional deformation and metamorphism.
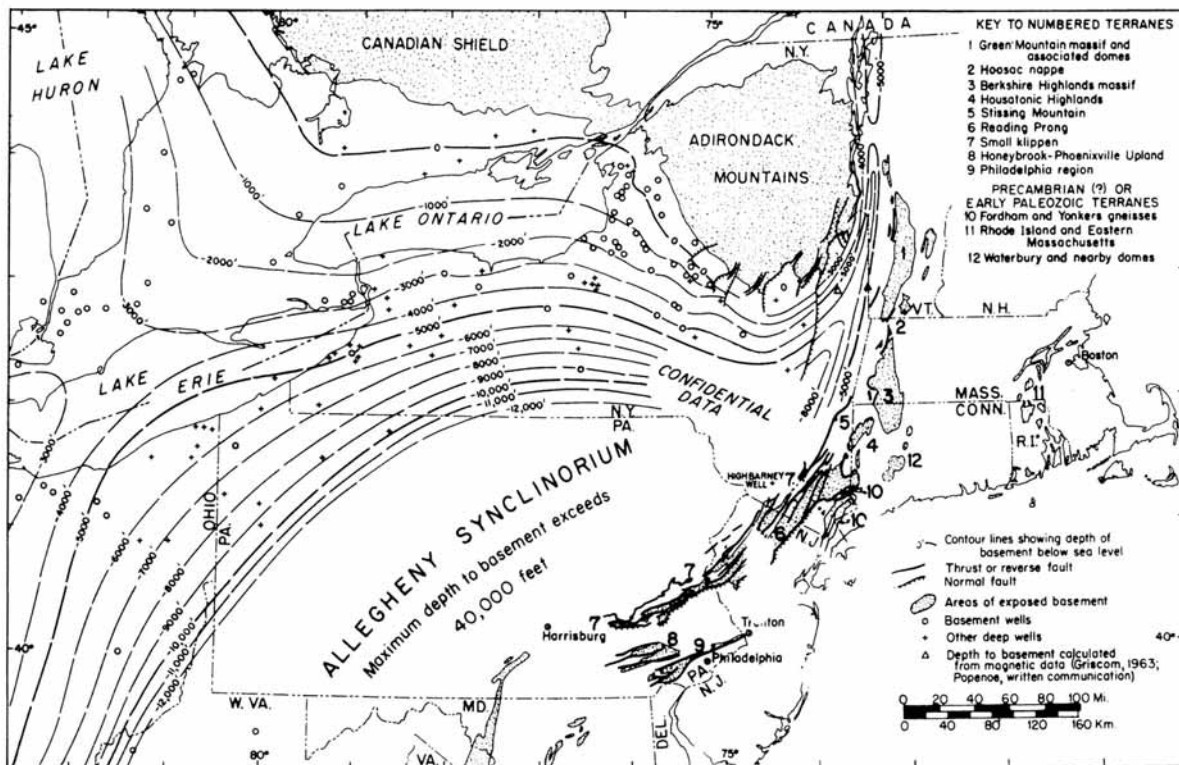

Figure 11 - Configuration of Precambrian surface and areas of exposed basement (Isachsen, 1964).
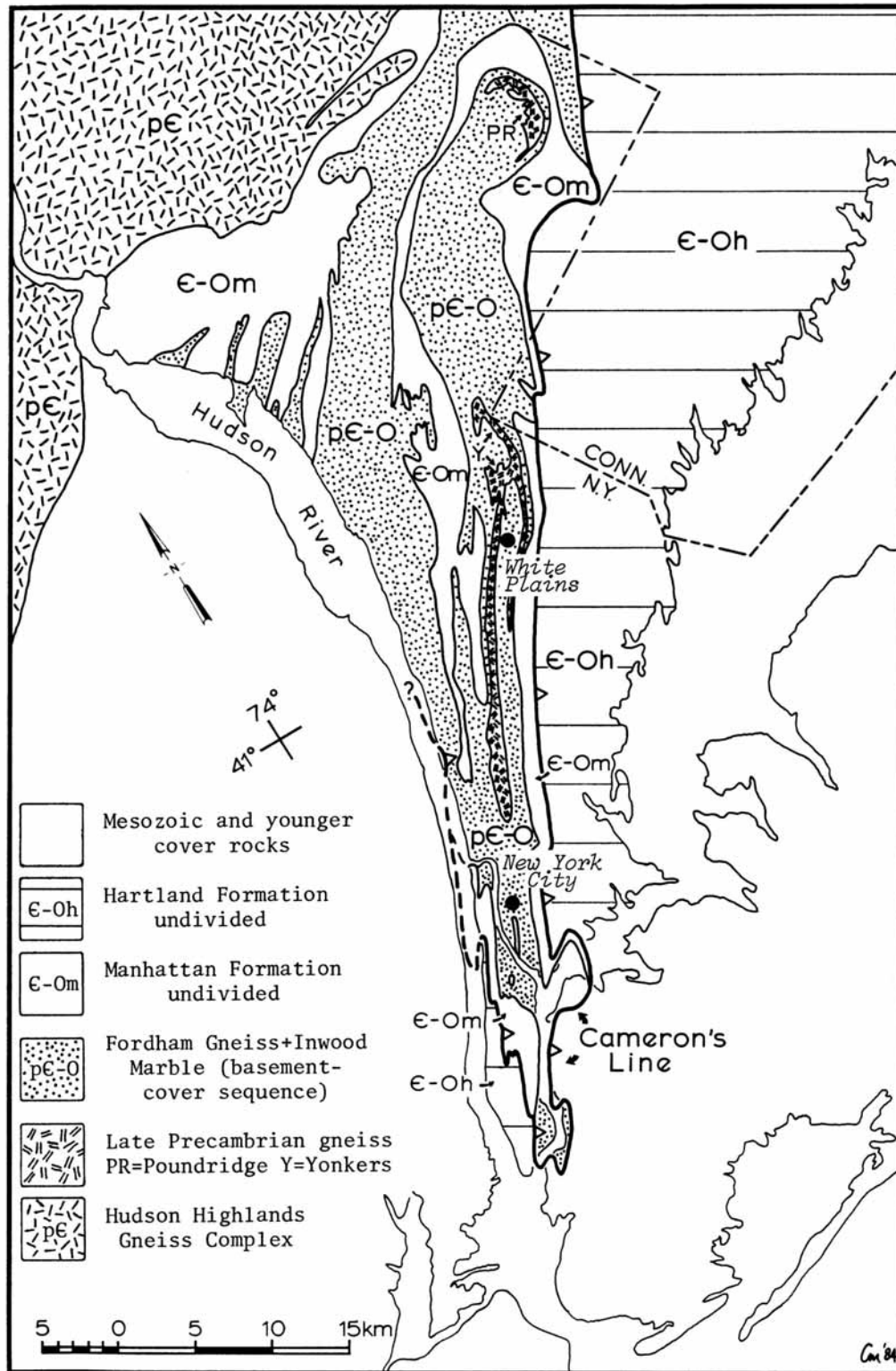
Figure 12 - Simplified geologic map of the Manhattan Prong showing the distribution of metamorphic rocks (Layers I and II) ranging from Proterozoic Y through Early Paleozoic in age. Most faults and intrusive rocks have been omitted (Mose and Merguerian, 1985)

The rifting of the Proterozoic Y craton in latest Proterozoic time thus sets the stage for the first of the Paleozoic trailing-edge continental margins of eastern North America. This trailing edge of the Iapetus Ocean, (or passive margin I) was to receive clastic, then carbonate sediments of Layer IIA. (See Tables 1 and 2.) Thus, early into the Paleozoic Era, this part of the Appalachian mountain belt region became the trailing edge of a continental plate, a passive continental margin (Figure 13) adjacent to the ancestral Atlantic Ocean (Iapetus). This tectonic setting persisted until the Taconic orogeny, late in the middle Ordovician Period. Interestingly, the contemporary passive-continental-margin setting of eastern North America, [deformed Paleozoic and older basement covered by essentially nondeformed Mesozoic and younger sediments that were (and continue to be) deposited as the margin subsides toward an ocean basin to the east] more or less duplicates that of Early Paleozoic time!
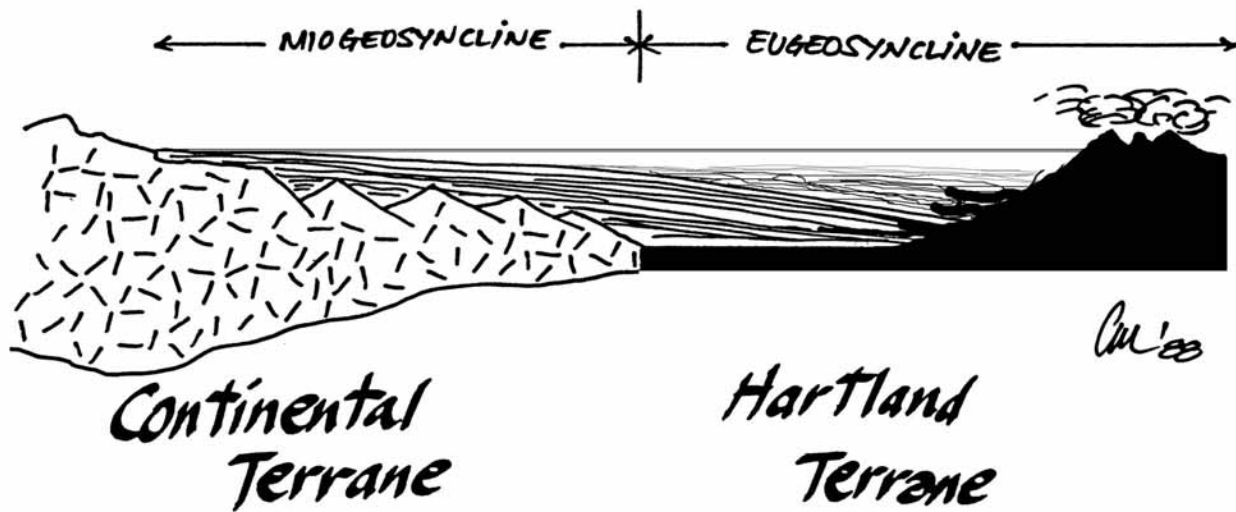

Figure 13 - Diagrammatic sketch of the passive margin of eastern North America in Early Paleozoic time showing the contrast in miogeosynclinal and eugeosynclinal depositional areas.

Layers IIA and IIB: Cambro-Ordovician Strata

As we examine rocks in Central Park today, we will walk upon the metamorphosed products of two contrasting paleogeographic-paleotectonic regimes: (1) sediments deposited on an ancient passive continental margin, which lasted from early in the Cambrian Period until the medial Ordovician Period (Figure 14) and which featured a carbonate-platform interior (now designated as the Sauk Sequence) that was bordered on the east by a continental-rise prism of fine-textured terrigenous sediment (Taconic Sequence) and an oceanward volcanic source [Layers IIA(W) and (E)]; and (2) the filling of a foreland basin, part of an actively converging continental margin [Layer IIB; now designated as the Tippecanoe Sequence], which commenced later in the Ordovician Period and extended through at least the end of the Ordovician period. The Tippecanoe Sequence holds the eroded products of important convergent mountain-building event (the Taconic orogeny), which featured mountains that were elevated where formerly the

sea stood and that eventually, during the Silurian and Devonian periods, shed coarse sediments [Layer III] westward toward the interior of the continent. (See Tables 1, 2.)
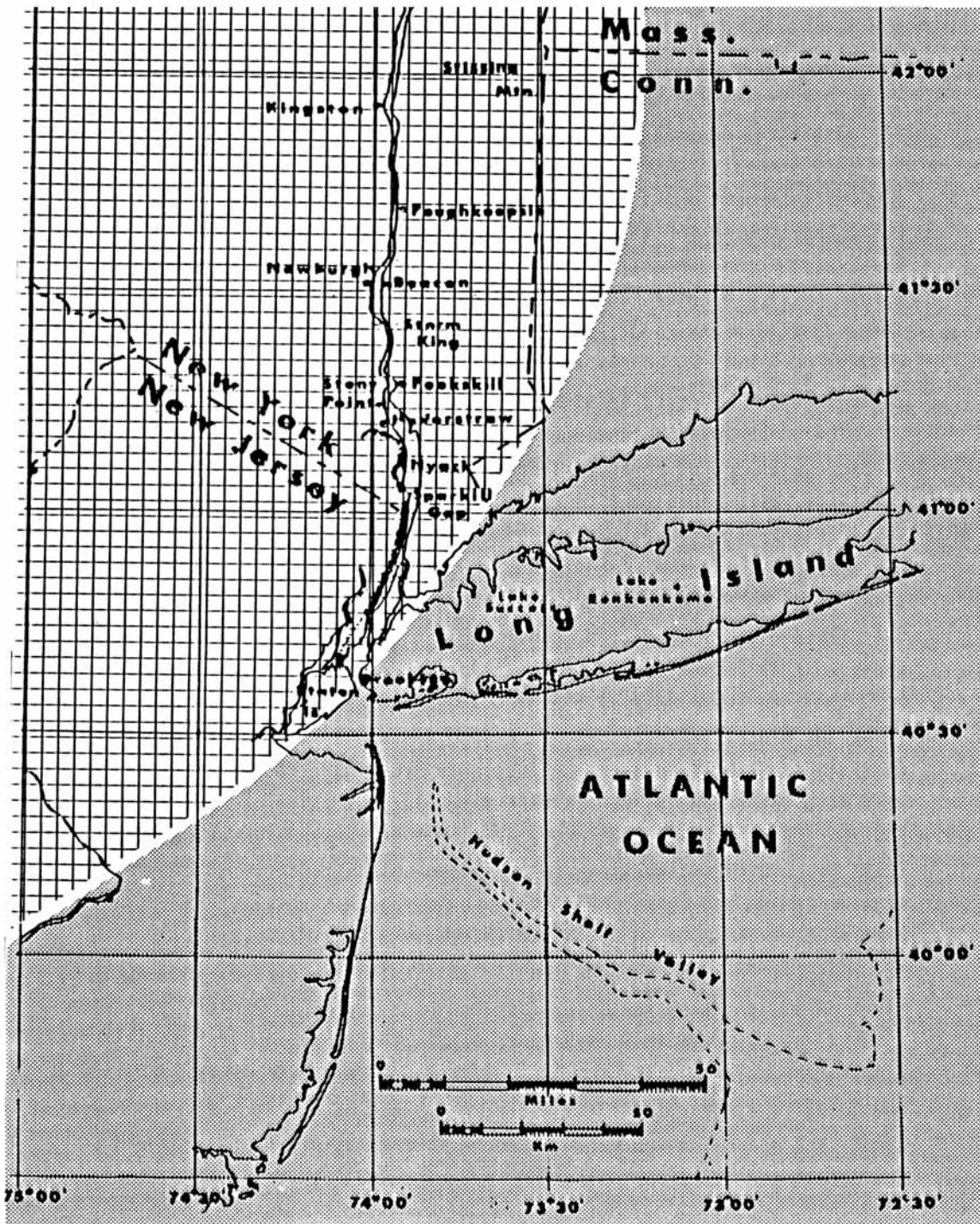

Figure 14 - Boundary between carbonate platform (pattern of squares) and deeper-water area to the east where terrigenous sediments were deposited (shaded), during the Cambrian and early part of the Ordovician periods. JES diagram.

The important change from a passive continental margin to a convergent margin involved overthrusts toward the continent, slope reversal, and geographic rearrangements. The first of the overthrusts toward the continent broke inboard of the former shelf edge and brought felsic continental basement rocks above the muds on the floor of the foreland basin where the Tipppecanoe Sequence was accumulating. Later, the Taconic allochthons were emplaced, whereby the the fine-textured terrigenous sediments of Layer IIA(E), deposited in the vicinity of the ancient continental rise and oceanward (Taconic Sequence), were displaced physically above carbonates and clastics of the Sauk Sequence [Layers IIA(W) and IIB]. Two important thrust surfaces are connected with the Taconic Sequence: (1) the so-called "Taconic basal thrust," which brings the continental-rise sediments up onto the former shelf area (specifically onto the foreland-basin-filling sediments that overlie the shelf carbonates; the westernmost boundary between "Taconic rocks" and "shelf rocks" has been referred to as "Logan's Line") and (2) a major thrust within the Taconic Sequence along which deep-ocean sediments have been thrust westward over continental-rise sediments (the boundary between the metamorphic rocks formed from these two contrasting protoliths is Cameron's Line).

Synorogenic flysch [Layer IIB] above Layer IIA actively filled the rapidly subsiding foreland basin. The evidence for this change consists of karst landscape and karst-depression-filling breccias at the top of the basal limestone of the Tippecanoe Sequence and the eventual covering of this karst surface with graptolite-bearing Tippecanoe-Sequence shales [Layer IIB] (Figure 15). A complicating factor is that the overthrust sheets (including the Taconic allochthon) were emplaced along the sea floor where the foreland-basin fill was accumulating. Modern hypotheses contend that the loading of the continental margin by the advancing Taconic allochthon may have caused the foreland basin to subside. According to CM, only a small part of the Manhattan Schist formation represents the metamorphosed clastics that were part of this foreland-basin filling material. The main body consists of two thrust sheets consisting of "Taconic" rocks: a lower sheet consisting of metamorphosed continental-rise sediments and an upper sheet, of metamorphosed deep-ocean sediments.

In terms of large stratigraphic units, the Cambro-Ordovician carbonate succession (Layer IIA(W)), deposited on the former continental platform, is collectively designated as the Sauk Sequence. Local representatives of the Sauk Sequence include the Wappinger Group (whose name was taken from Wappinger Creek, E and S of Poughkeepsie) or Kittatinny Group (New Jersey name), and their metamorphosed equivalents. From Connecticut northward, the Sauk carbonates have been metamorphosed into marble, locally named Woodville, Vermont, Stockbridge, and Woodbridge marbles. In the New York City region, this marble is the Inwood Marble. These marbles probably include not only the Sauk carbonates, but also the basal limestone of the overlying Tippecanoe Sequence. The vast sheet of Sauk carbonates is known elsewhere by other names. (See Figure 14.) It is the famous oil-bearing Arbuckle Group of Oklahoma and Kansas; the Ellenburger Group of Texas; and the Knox Group of the southern Appalachians. In general, the Sauk carbonates consist of quartzose dolomite, and dolomitic rocks of Cambrian and Early Ordovician age. In the marginal troughs, they are underlain by Lower Cambrian quartzose clastic rocks. Outside the marginal troughs, the basal clastics are of Late Cambrian age. The Cambrian clastic strata are known as the Cheshire Quartzite in Massachusetts, the Poughquag Quartzite in New York, and as the Lowerre Quartzite in the

vicinity of New York City. Farther south, correlatives include the Hardyston Quartzite in New Jersey and still farther south, in Pennsylvania, the Setters Quartzite.
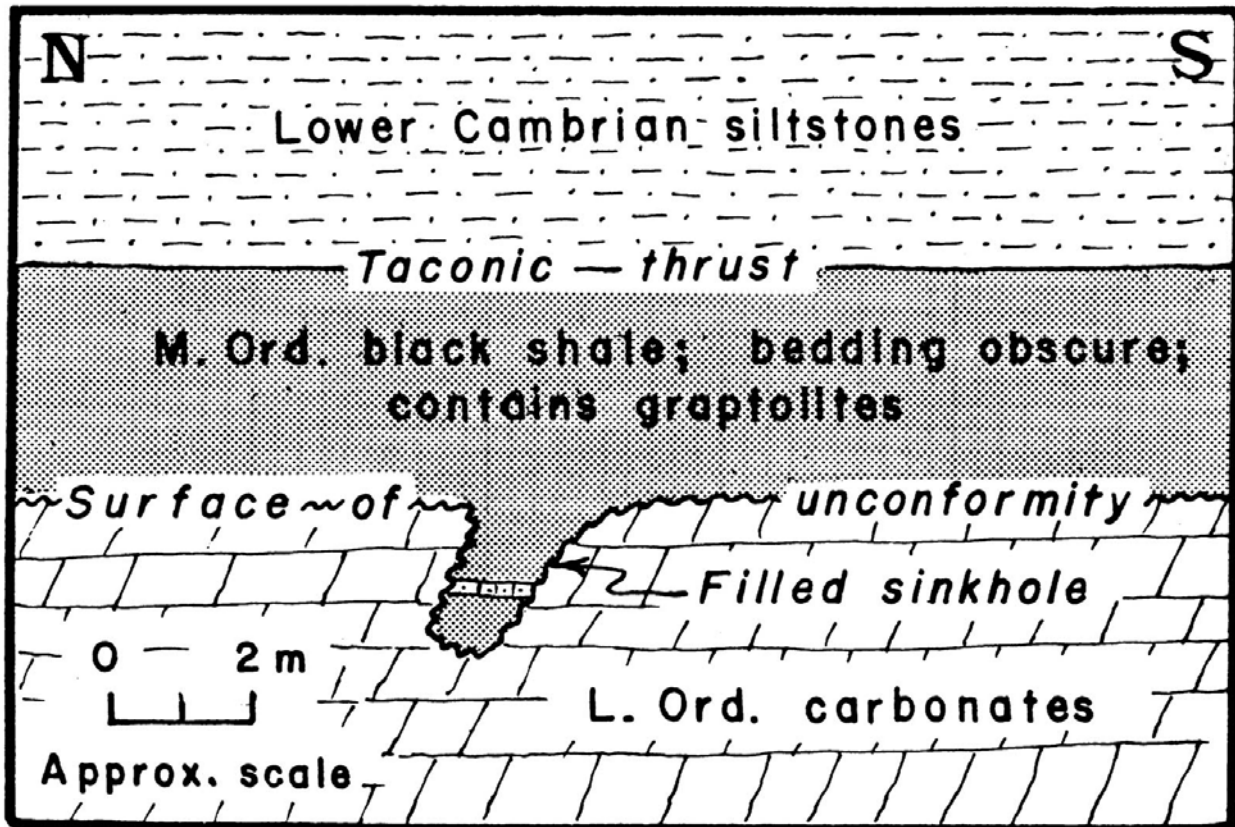

Figure 15 - West face of Bald Mountain, Washington County, New York, showing the three major units of the "Taconic Problem" in contact. The surface of unconformity proves that some terrigenous sediments do not have to be in thrust contact with the Cambro-Ordovician carbonate succession. The Taconic thrust of Cambrian siltstones against Middle Ordovician shales took place on the sea floor. Thus, locally, there is no major indication of thrusting (no mylonite, no contrast in minor structures above and below the thrust - thus nothing to show the presence of a thrust to investigators who do not pay attention to the fossils). Based on Sanders, Platt, and Powers (1961). Sketch by JES.

        Exposures of the Lowerre Quartzite have never been found in Manhattan or the Bronx. As a result of sediment covering, construction, as well as its very local development, the Lowerre is no longer exposed on the surface. In fact, in comparison to areas immediately to the north and south in the Appalachian range, Cambrian clastic rocks are rare in the vicinity of New York City. Perhaps the New York City area was emergent during early Cambrian times and shed coarse clastic sediment rather than collecting it. CM has encountered a thin basal quartzite in drill core from the subsurface of the Bronx and Manhattan.

Bedrock Stratigraphy of New York City

The bedrock underlying Manhattan includes the Fordham Gneiss, Lowerre Quartzite, Inwood Marble, and various schistose rocks formally included in the Manhattan Schist. These metamorphosed, Lower Paleozoic bedrock units are found west of Cameron's Line, a major tectonic boundary in New England. Together, they constitute the autochthonous miogeosynclinal basement-cover sequence of the New England Appalachians (pЄ-O in Figure 12) and are the products of metamorphism of sediments formerly deposited on Proterozoic crust. Rocks found east of Cameron's Line in western Connecticut and southeastern New York belong to the Hartland Formation (Cameron 1951, Gates 1951, Rodgers and others 1959, Merguerian 1977, 1983b) or Hutchinson River Group (Seyfert and Leveson 1968, 1969; Levesen and Seyfert 1969), or Pelham Bay Member of the Hartland Formation (Baskerville 1982a). In contrast to the basement-cover sequence, the Hartland Formation consists of a sequence of metamorphosed eugeosynclinal rocks whose protoliths were deposited on oceanic crust (Є-Oh in Figure 12) which became accreted to North America during the Medial Ordovician Taconic orogeny (Hall, 1979; Merguerian 1979, 1983; Merguerian and others, 1984; Robinson and Hall, 1979). To the west of Cameron's Line, in Manhattan, rocks with lithologic affinities transitional to these extremes crop out.

Merrill (1890) established the name Manhattan Schist for the well-exposed schists of Manhattan Island. Hall's (1968a, b, c) mapping in White Plains established subdivisions of the Manhattan Schist into two basic units. The autochthonous Manhattan A, which was originally deposited as part of the Tippecanoe Sequence overlying the basal Tippecanoe limestone that forms the topmost unit of the Inwood marble and the allochthonous (transported rocks not found where deposited) Manhattan B and C members (Figure 10). Hall (1976) suggested that the Manhattan C (schist) and B (interlayered amphibolite unit) were Early Cambrian (or possibly older) in age, and thus are parts of the Taconic Sequence (Layer IIA(E) in our scheme) and were deposited below aluminous schist and granofels of the Hartland Formation. In Figure 12, Manhattan A is included in the basement-cover sequence (pЄ-O) and Manhattan B and C are designated Є-Om. Merguerian (1983a, 1985a) interprets the Manhattan B an C as a slope-rise sediments that were deposited continentward of the sedimentary protoliths of the Hartland Formation and are now separated from them by Cameron's Line. Thus, in contrast to Hall's (1976, 1980) views, CM regards the Manhattan B and C and the Hartland as being essentially coeval tectonostratigraphic units.

To answer a question posed by Dr. Patrick Brock of Queens College, we are not sure how basaltic volcanics become interstratified with Cambro-Ordovician slope/rise sediments but offer two possible models. Basalts may represent offscraped oceanic crust tectonically imbricated within the subduction complex during the Taconic orogeny. This model would suggest no stratigraphic significance to the mafic horizon near the base of Manhattan C and careful mapping may indicate that Hall's (1968) call on the stratigraphic position of the mafic unit may be oversimplified. A second model would place the basalt into the slope/rise sediments as a sill-like intrusive sheet. In this case, the basalts would be the result of Cambrian or Eocambrian rifting and antedate the Taconic orogeny. Perhaps they are equivalent to basalts found in the Rensselaer Graywacke.

Strong evidence for three subdivisions and possibly allochthony within the Lower Paleozoic schists exists in New York City (Merguerian, 1981, 1983; Mose and Merguerian, 1985). On the basis of lithostratigraphic- and structural evidence, most of the exposed schist on Manhattan Island is interpreted as the metamorphosed part of a transitional slope-rise sequence (C-Om) and as the eugeosynclinal deep-water oceanic Hartland Formation (C-Oh), not as the metamorphosed stratigraphically youngest unit, the foreland-basin-filling Tippecanoe Sequence, as was suggested in all "pre-plate tectonics" bedrock interpretations!

Based on his detailed mapping, CM divides the schist on Manhattan Island into three, lithologically distinct, structurally imbricated, lithostratigraphic units of kyanite- to sillimanite metamorphic grade that plunge toward the south (Figure 16). The structurally lowest unit (Om), crops out in northern Manhattan and the west Bronx. This unit is composed of brown-to rusty-weathering, fine- to medium-textured, typically massive, muscovite-biotite-quartz-plagioclase-kyanite-sillimanite-garnet schist containing interlayers centimeters- to meters thick of calcite+diopside marble. The minerals are listed in order of decreasing relative abundance. This lower unit is lithically correlative with the Middle Ordovician Manhattan member A of Hall (1968a) because it "looks like it" and is found interlayered with the underlying Inwood at two localities (1) at Inwood Hill Park and (2) Grand Councourse and I-95, The Bronx. Near the schist-Inwood contact the carbonate rocks contains layers of calcite marble (probably metamorphosed Balmville, the basal limestone of the Tippecanoe Sequence). Because it is interpreted as being autochthonous (depositionally above the Inwood Marble), CM informally refers to it as "the Good-Old Manhattan Schist" and assigns it a middle Ordovician age as part of the Tippecanoe Sequence. (JES notes that this is in contrast to the older, "Bad-New Manhattan Schist" mentioned above.)

The lower schist unit and the Inwood Marble are structurally overlain by the middle schist unit (C-Om) which forms the bulk of the "schist" exposed on the Island of Manhattan (Figure 16). The middle schist unit consists of rusty- to sometimes maroon-weathering, medium- to coarse-textured, massive biotite-muscovite-plagioclase-quartz-garnet-kyanite-sillimanite gneiss and, to a lesser degree, schist. The middle schist unit is characterized by the presence of kyanite+sillimanite+ quartz+magnetite layers and lenses up to 10 cm thick, cm- to m-scale layers of blackish amphibolite (metamorphosed basaltic rock), and quartzose granofels. The middle unit is lithologically identical to Hall's Manhattan B and C and the Waramaug and Hoosac formations of Cambrian to Ordovician ages in New England (Hatch and Stanley, 1973; Hall, 1976; Merguerian, 1981a, 1983b). These rocks are inferred to represent metamorphosed Cambrian to Ordovician sedimentary- and minor volcanic rocks formed in the transitional slope- and rise environment of the Early Paleozoic continental margin of ancestral North America.

The structurally highest, upper schist unit (C-Oh) is dominantly gray-weathering, fine- to coarse-textured, well-layered muscovite-quartz-biotite-plagioclase-kyanite-garnet schist, gneiss, and granofels with cm- and m-scale layers of greenish amphibolite + garnet. The upper schist unit, which based on CM's study of more than 500 outcrops in Manhattan and the Bronx, and a multitude of drill cores and construction excavations, underlies most of the western- and southern third of Manhattan, and the eastern half of the Bronx and is lithologically identical to the Cambrian and Ordovician Hartland Formation of western Connecticut and southeastern New
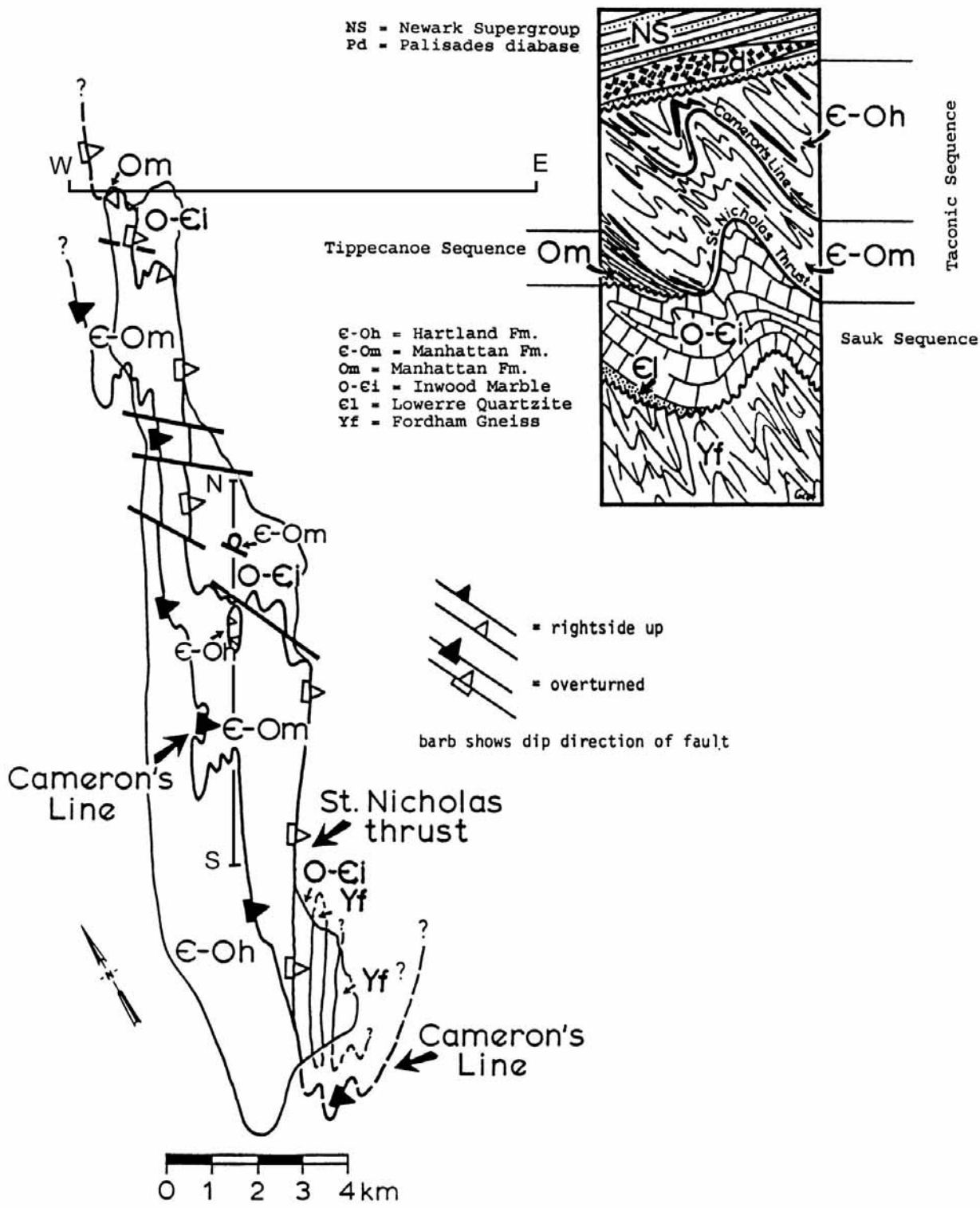
Figure 16 - Geologic map of Manhattan Island showing a new interpretation of the stratigraphy and structure of the Manhattan Schist. Drawn and mapped by C. Merguerian.

York. On this basis, CM correlates them with the Hartland. Therefore, CM has extended the name Hartland into New York City. Accordingly, CM infers that together they represent metamorphosed deep-oceanic shales, interstratified graywackes, and volcanic rocks formed adjacent to North America during Early Paleozoic time.

In summary, the three distinctive mappable units of the "Manhattan Schist" represent essentially coeval foreland-basin-fill- (Om), transitional slope/rise- (Ꞓ-Om), and deep-water (Ꞓ-Oh) lithotopes that were juxtaposed when the ancestral North American shelf edge was telescoped in response to closure of the proto-Atlantic (Iapetus) ocean during the Taconic orogeny (Figure 17). Regional correlation suggests, then, that the higher structural slices of the Manhattan Schist are older, or possibly the same age as, the lower unit (Om). The structural evidence that CM uses to define the contacts among the three Manhattan "schists" is described below. The discussion of that structural evidence is located after the following general introduction to geologic structure that we have included as a matter of convenience to readers whose knowledge of structural geology may be in need of a bit of refreshing.
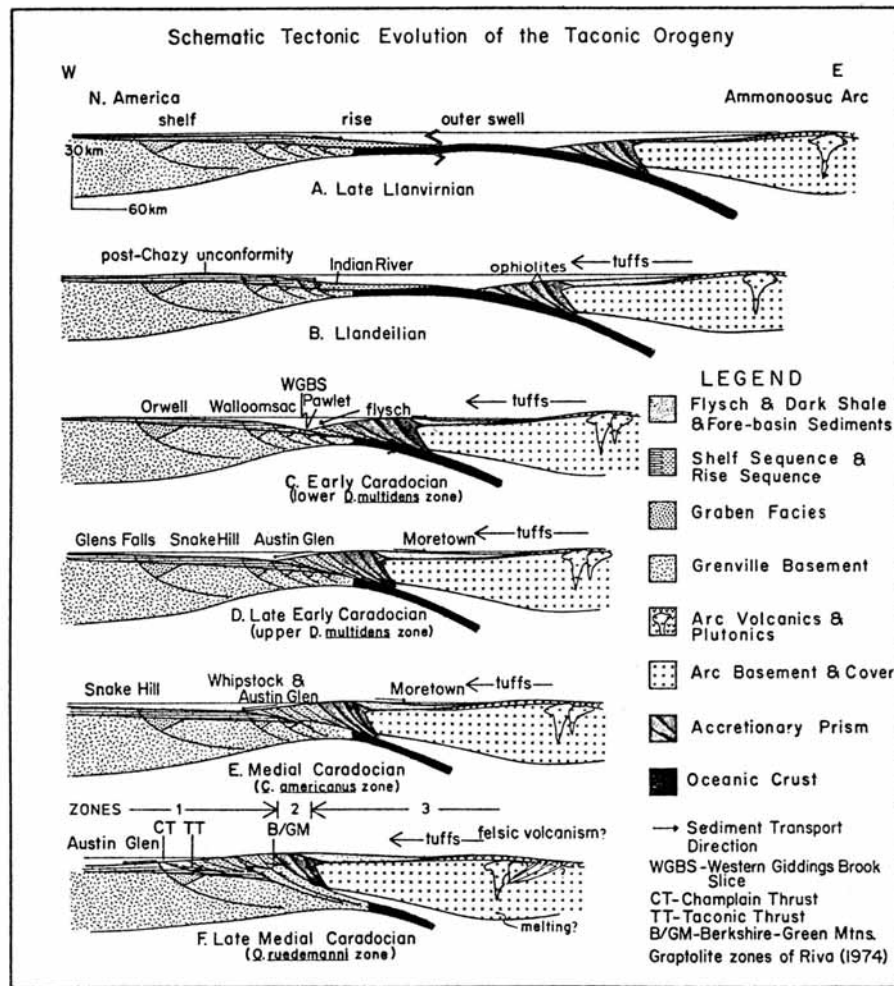

Figure 17 - Sequential tectonic cross sections for the Taconic orogeny in New England. From Rowley and Kidd (1981).

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Geologic Structure--A Primer

Geologists use terminology to confuse the layman and to enable them to amass a huge library of terms that are undeniably useless in most social situations. Our On-The-Rocks trips are an exception. Luckily, and we will not try to bury you in a mountain (how about a deeply eroded mountain range?) of terms to help you understand the major types of structures and geologic features that you will read- and hear about today. But, if you are to understand what we are talking about, you need to know some important definitions. In the following section, we describe folds, faults, surfaces of unconformity, sedimentary structures, structures in sedimentary- vs. metamorphic rocks, and tectonostratigraphic units.

We begin with some concepts and definitions based on the engineering discipline known as strength of materials. Given today's sophisticated laboratory apparatus, it is possible to subject rocks to temperatures- and pressures comparable to those found deep inside the Earth.

Imagine taking a cylinder of rock out of the Earth and torturing it in a tri-axial compression machine to see what happens. Some geologists get a big charge out of this and tell us (the field geologists) that they really understand how rocks behave under stress. [CM thinks they need to perform these experiments over a longer time frame than a few generations of siblings will allow and thus relies more on field observation and inference than from rock-squeezing data to gain a feel for the complex nature of how rocks are deformed in nature.]

Despite the limitations of the experimental work, measurements in the laboratory on specimens being deformed provide some fundamental definitions. One key definition is the elastic limit, which is the point at which a test specimen no longer returns to its initial shape after the load has been released. Below the elastic limit, the change of shape and/or volume (which is known as strain) is proportional to the stress inside the specimen. Above the elastic limit, the specimen acquires some permanent strain. In other words, the specimen has "failed."

When differential force is applied slowly, rocks fail by flowing. This condition is defined as behaving in a ductile fashion (toothpaste being squeezed out of a tube is an example of ductile behavior). Folds are the result of such behavior. If the force is applied under low confining pressure or is applied rapidly (high strain rates), rocks do not flow, but fracture. This kind of failure is referred to as rocks behaving in a brittle fashion (as in peanut brittle). The result is faults or joints. Once a brittle failure (fracture) has begun, it will propagate, produce offset, and form a fault surface that will show elongate gouges (called slickensides) that may possess asymmetric linear ridges that enable one to determine the relative motion between the moving sides.

In some cases, during deformation, rocks not only undergo simple strain, but also recrystallize. New metamorphic minerals form and newly formed metamorphic minerals acquire a parallel arrangement. More on mmetamorphic textures later. From the laboratory studies of rock deformation, a few simple relationships are generally agreed upon regarding brittle- and ductile faulting and these are discussed below.

When subjected to differential forces, under high confining pressures and elevated temperatures, rocks (like humans) begin to behave foolishly, squirming in many directions and upsetting the original orientation of primary- or secondary planar- and linear features within them. Geologists try to sort out the effects of deformation by working out the order in which these surfaces or linear features formed using a relative nomenclature based on four letters of the alphabet: D, F, S, and M. Episodes of deformation are abbreviated by (Dn), of folding by (Fn), of the origin of surfaces (such as bedding or foliation) by (Sn), and of metamorphism by (Mn), where n is a whole number starting with 1 (or in some cases, with zero). Bedding is commonly designated as S_0 (or surface number zero) as it is commonly overprinted by S_1 (the first foliation). To use this relative nomenclature to describe the structural history of an area, for example, one might write: "During the second deformation (D_2), F_2 folds formed; under progressive M_1 metamorphic conditions, an axial-planar S_2 foliation developed."

In dealing with the geologic sturctures in sedimentary rocks, the first surface one tries to identify positively is bedding or stratification. The boundaries of strata mark original sub-horizontal surfaces imparted to sediments in the earliest stage of the formation of sedimentary rock. Imagine how such strata, buried by the weight of overlying strata and laterally compressed by the advance of lithospheric plates, are subjected to the differential force necessary for folds to form. Contrary to older ideas, we now realize that vertical burial cannot cause regional folds (although small-scale slumping and stratal disharmony are possible). Rather, tangential force must be applied to provide the driving force to create folds and faults.

It's time to turn to some geometric aspects of the features formed as a result of deformation of rocks in the Earth. We start with folds.

Folds

If layers are folded into convex-upward forms we call them anticlines. Convex-downward fold forms are called synclines. In Figure 18, note the geometric relationship of anticlines and synclines. Axial planes (or axial surfaces) physically divide folds in half. Note that in Figure 18 the fold is deformed about a vertical axial surface and is cylindrical about a linear fold axis that lies within the axial surface. The locus of points connected through the domain of maximum curvature of the bedding (or any other folded surface of the fold) is known as the hinge line (which is parallel to the fold axis). This is geometry folks; we have to keep it simple so geologists can understand it.

In eroded anticlines, strata forming the limbs of the fold dip away from the central hinge area or core (axis) of the structure. In synclines, the layers forming the limbs dip toward the hinge area. Given these arrangements, we expect that in the arches of eroded anticlines, older stratigraphic layers will peek through whereas in the eroded troughs of synclines, younger strata will be preserved.

In metamorphic terranes, field geologists are not always sure of the correct age relationships of the metamorphosed strata. Therefore, it is helpful to make use of the general terms antiform and synform which describe the folds by whether they are convex upward

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(antiform) or concave upward (synform) but do not imply anything about the relative age of the strata within them.
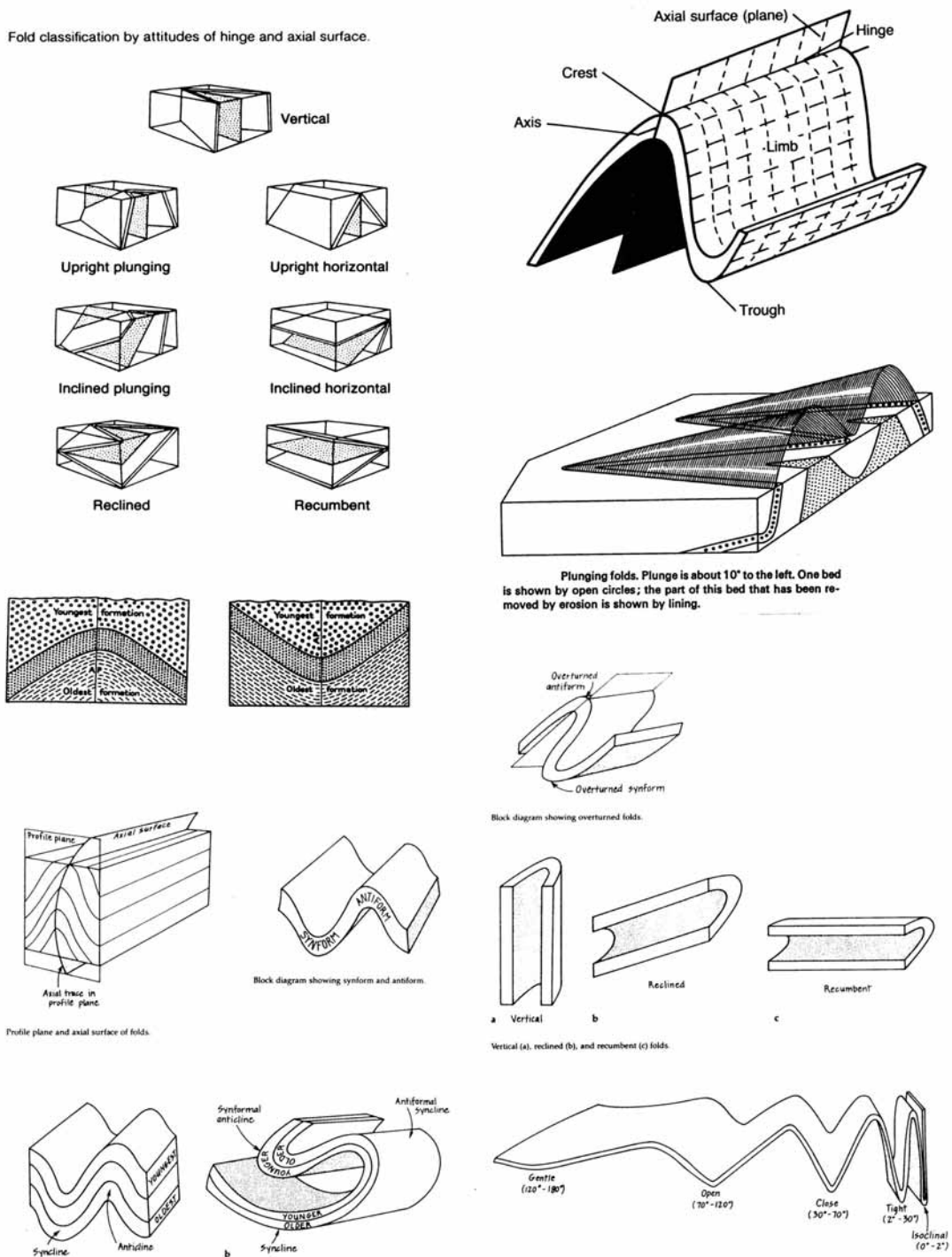

Figure 18 - Composite diagram from introductory texts showing various fold styles and nomenclature as discussed in the text.

Realize that in the upright folds shown in Figure 18, axial surfaces are vertical and fold axes, horizontal. Keep in mind that folding under metamorphic conditions commonly produces a penetrative mineral fabric with neocrystallized minerals (typically micas and amphiboles) aligned parallel to the axial surfaces of folds. Such metamorphic fabrics are called foliation, if primary, and schistosity, if secondary. Minerals can also align in a linear fashion producing a metamorphic lineation. Such features can be useful in interpreting a unique direction of tectonic transport or flow direction. Because folds in metamorphic rocks are commonly isoclinal (high amplitude-to- wavelength aspect ratio) with limbs generally parallel to axial surfaces, a penetrative foliation produced during regional dynamothermal metamorphism will generally parallel the reoriented remnants of stratification (except of course in the hinge areas of folds). Thus, in highly deformed terranes, a composite foliation + remnant compositional layering is commonly observed in the field. Departures from this common norm are important to identify as they tend to mark regional fold-hinge areas.

Folds could care less about the orientation of their axes or axial surfaces and you can certainly imagine that axial surfaces can be tilted, to form inclined or overturned folds. Or the axial surfaces may be sub-horizontal, in which case the term recumbent folds is used. In both overturned folds and recumbent folds, the fold axes may remain subhorizontal. (See Figure 18.) It is also possible for an axial surface to be vertical but for the orientation of the fold axis to range from horizontal to some angle other than 0° (thus to acquire a plunge and to produce a plunging fold). Possible configurations include plunging anticlines (or -antiforms) or plunging synclines (or -synforms). Vertical folds (plunging 90°) are also known; in them, the terms anticline and syncline are not meaningful. In reclined folds, quite common in ductile fault zones (see below), the fold axes plunge directly down the dip of the axial surface.

In complexly deformed mountain ranges, most folds show the effects of more than one superposed episode of deformation. As a result of multiple episodes of deformation, the ultimate configuration of folds can be quite complex (i. e., plunging folds with inclined axial surfaces and overturned limbs).

We need to mention one other point about the alphabet soup of structural geology. Seen in cross section, folds fall into one of three groups, the S's, M's, and the Z's. Usually only one variety of small folds will be found on a given limb of a larger fold. Therefore, if one notices a change in the pattern from S folds to Z folds (or vice versa), one should be on the lookout for a fold axis. The hinge area is dominated by M-folds (no sense of asymmetry).

One final note on folding -- it is generally agreed, in geologically simple areas, that axial surfaces form perpendicular to the main forces that produced the fold. Therefore, the orientation of the folds give some hint as to the direction of application of the active forces (often a regional indicator of relative plate convergence). In complex regions, the final regional orientation of the structures is a composite result of many protracted pulses of deformation, each with its unique geometric attributes. In these instances, simple analysis is often not possible. Rather, a range of possible explanations for a given structural event is commonly presented.

Faults

A fault is defined as a fracture along which the opposite sides have been displaced. The surface of displacement is known as the fault plane (or fault surface). The block situated below the fault plane is called the footwall block and the block situated above the fault plane, the hanging-wall block (Figure 19). Extensional force causes the hanging-wall block to slide down the fault plane producing a normal fault. Compressive forces drive the hanging-wall block up the fault plane to make a reverse fault. A reverse fault with a low angle ($<30°$) is called a thrust fault. In all of these cases, the slickensides on the fault will be oriented more or less down the dip of the fault plane. These, therefore, illustrate dip-slip motion.
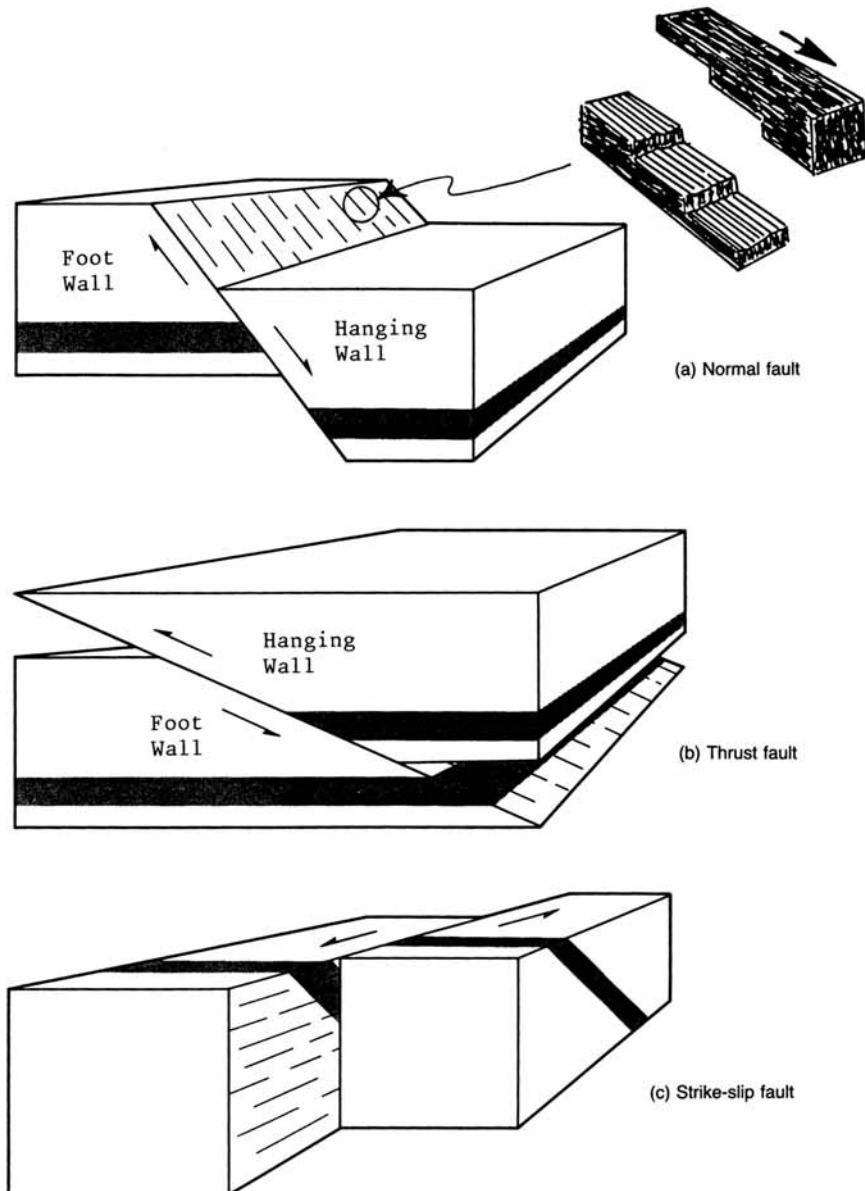
Figure 19 - Composite diagram from introductory texts showing the three main types of faults.

Rather than simply extending or compressing a rock, imagine that the block of rock is sheared along its sides (i. e., that is, one attempts to rotate the block about a vertical axis but does

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not allow the block to rotate). This situation is referred to as a shearing couple and could generate a strike-slip fault. (See Figure 19.) On a strike-slip-fault plane slickensides are oriented subhorizontally.

Only two kinds of shearing couples and/or strike-slip motion are possible: left lateral and right lateral. These are defined as follows. Imagine yourself standing on one of the fault blocks and looking across the fault plane to the other block. If the block across the fault from you appears to have moved to the left, the fault is left lateral. If it appears to have moved to the right, it is right lateral. Convince yourself that no matter which block you can choose to observe the fault from, you will get the same result! Naturally, complex faults show movements that can show components of dip-slip- and strike-slip motion, rotation about axes perpendicular to the fault plane, or reactivation in a number of contrasting directions or variety. This, however, is no fault of ours.

Tensional- or compressional faulting resulting from brittle deformation, at crustal levels above 10 km, is accompanied by seismicity and the development of highly crushed and granulated rocks called breccias and cataclasites (including fault gouge, fault breccia, and others). Starting at roughly 10 to 15 km and continuing downward, rocks under stress behave aseismically and relieve strain by recrystallizing during flow. These unique metamorphic conditions prompt the development of highly strained (ribboned) quartz, feldspar porphyroclasts (augen), and frayed micas, among other changes, and results in highly laminated rocks called mylonites. The identification of such ductile fault rocks in complexly deformed terranes can be accomplished only by detailed mapping of metamorphic lithologies and establishing their geometric relationship to suspected mylonite zones. Unfortunately, continued deformation under load often causes early formed mylonites to recrystallize and thus to produce annealed mylonitic textures (Merguerian, 1988), which can easily be "missed" in the field without careful microscopic analysis. Cameron's Line, a recrystallized ductile shear zone showing post-tectonic brittle reactivation, is an original ductile fault zone (mylonite) having a complex geologic history.

Over the years, field geologists have noted special geologic features associated with thrust faults. Because they propagate at low angles with respect to bedding, thrusts commonly duplicate strata. In addition, thrust faults can displace strata for great distances and wind up transporting rock deposited in one environment above rocks deposited in markedly disparate environments. In such cases, we call the displaced strata of the upper plate above a thrust fault an allochthon or describe an entire displaced sequence of strata as an allochthonous terrane. (See Tectonostratigraphic Units below.) In other words, allochthonous rocks were not originally deposited where they are now found. By contrast, regions consisting of rock sequences that were originally deposited where they are now found constitute an autochthon or autochthonous terrane.

Interesting geometric patterns result from the erosion of overthrust sheets of strata that have been folded after they were overthrust. If a "hole" has been eroded through the upper plate (allochthon), we can peer downward through the allochthon and see the underlying autochthon exposed in a window (also known as a fenster, the German word for window, or a thrust inlier) surrounded by the trace of the thrust fault that was responsible for the dislocation (Figure 20).

By contrast, if most of the upper plate has been eroded, only a remnant outlier or klippe may remain. (See Figure 20.) Both klippen and windows produce similar map-scale outcrop patterns. The difference is that the thrust surface typically dips toward the center of a klippe (a remnant of the allochthon) and away from the center of window (which shows a part of the underlying autochthon).
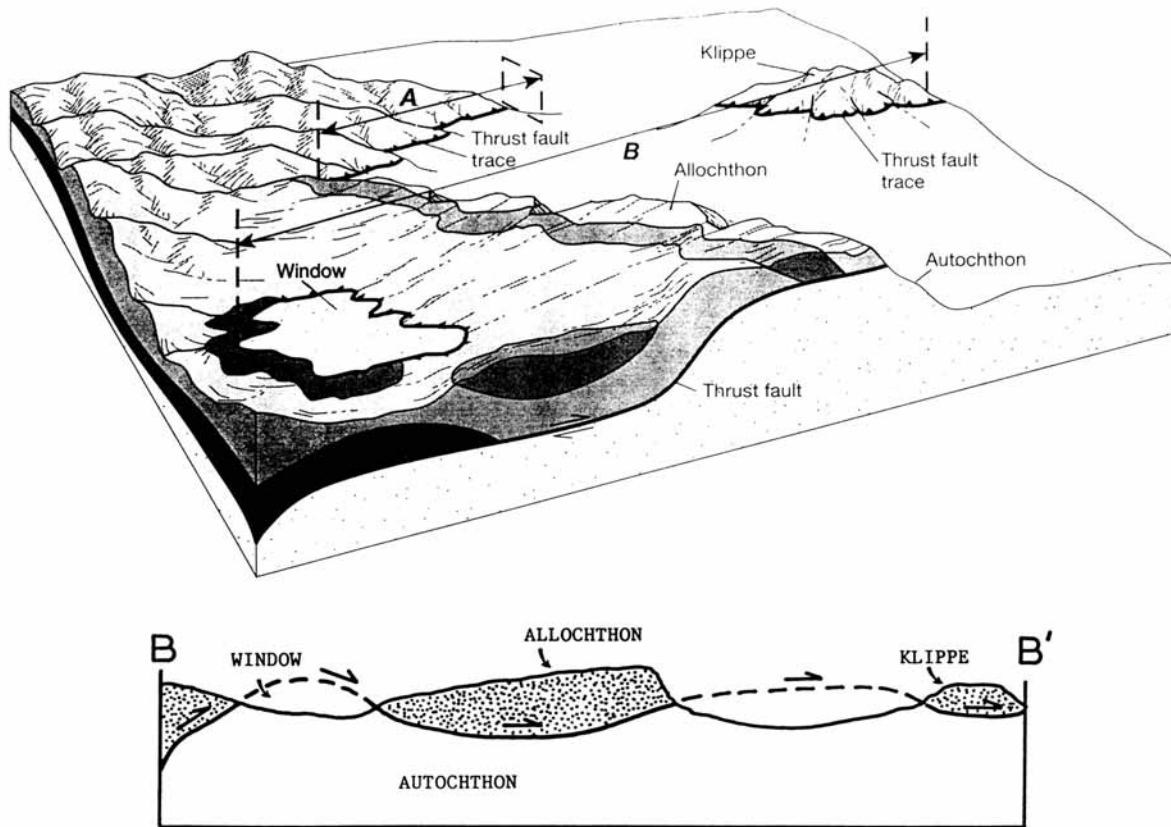

Figure 20 - Block diagram illustrating the relationships between allochthons, autochthons, klippen, and windows. (Twiss and Moores, 1992, p. 99) with section B-B' drawn by CM.

During episodes of mountain building associated with continuous subduction and/or collisions near continental margins, thrusting is typically directed from the ocean toward the continent. Accordingly, one of the large-scale effects of such periods of great overthrusting is to impose an anomalous load on the lithosphere which causes it to subside and form a foreland basin. These basins receive tremendous quantities of sediment which fill the basin from sediment derived from erosion of uplifted areas within the active collision zone. In the late stages of convergence, forces transmitted from the collision zone into the developing foreland basin create a diachronous secondary stage of folding and continent-directed overthrusting of the strata filling the foreland basin.

Surfaces of Unconformity

Surfaces of unconformity mark temporal gaps in the geologic record and commonly result from periods of uplift and erosion. Such uplift and erosion is commonly caused during the terminal phase of regional mountain-building episodes. As correctly interpreted by James Hutton at the now-famous surface of unconformity exposed in the cliff face of the River Jed (Figure 21), such surfaces represent mysterious intervals of geologic time where we really do not have a clue as to what went on! By looking elsewhere, the effects of a surface of unconformity of regional extent can be recognized and piecemeal explanations of evidence for filling in the missing interval may be found.
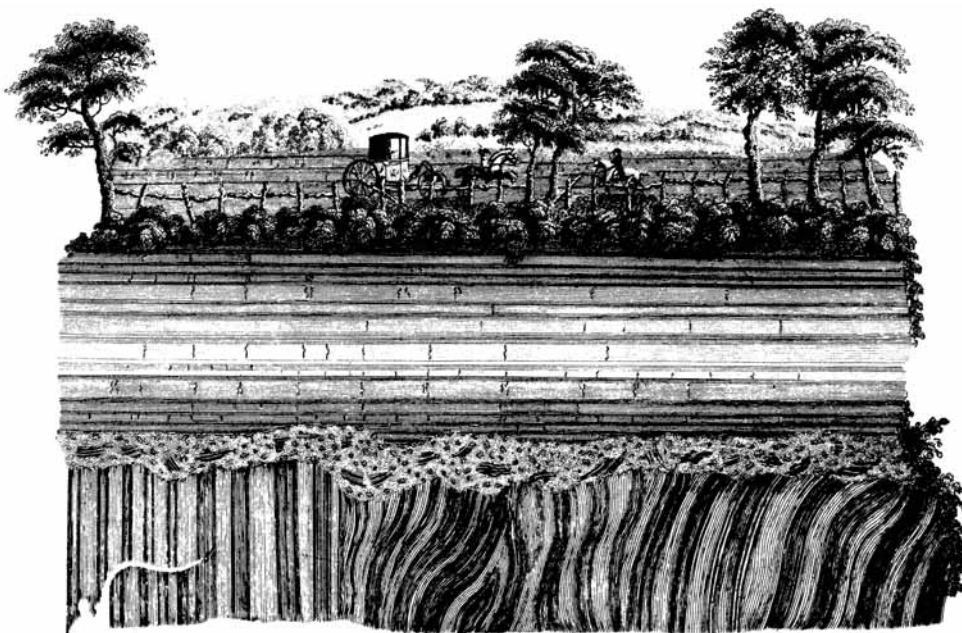

Figure 21 - Unconformity with basal conglomerate along the River Jed, south of Edinburgh, Scotland. From James Hutton's "Theory of the Earth", (1795).

Following the proposal made in 1963 by L. L. Sloss, surfaces of unconformity of regional extent within a craton are used as boundaries to define stratigraphic Sequences.

Sedimentary Structures

During deposition in a variety of environments, primary- and secondary sedimentary structures can develop above-, below-, and within strata. During normal deposition, or settling from a fluid in a rainfall of particles, massive, essentially poorly stratified successions may result. The presence of strata implies a change in deposition and as a result most geologists appreciate the significance of layering in sedimentary rocks as marking CHANGE in big letters, be it a change in parent area of the sediment, particle size, or style of deposition. Thus, bedding can best be viewed as marking the presence of mini-surfaces of unconformity (diastems). During high-energy transport of particles, features such as cross beds, hummocky strata, asymmetric current ripple marks, or graded beds result. Cross- and hummocky bedding, and asymmetric current ripple marks are deposited by moving currents and help us unravel the

paleocurrent directions during their formation. Graded beds result from a kind of a "lump-sum distribution" of a wide range of particles all at once (usually in a gravity-induced turbidity flow). Thus, graded beds show larger particle sizes at the base of a particular layer "grading" upward into finer particles.

Secondary sedimentary features are developed on already deposited strata and include mud (or desiccation) cracks, rain- drop impressions, sole marks, load-flow structures, flame structures, and rip-up clasts. The last three categorize effects produced by a moving body of sediment on strata already in place below. A composite diagram illustrating these common structures is reproduced in Figure 22.
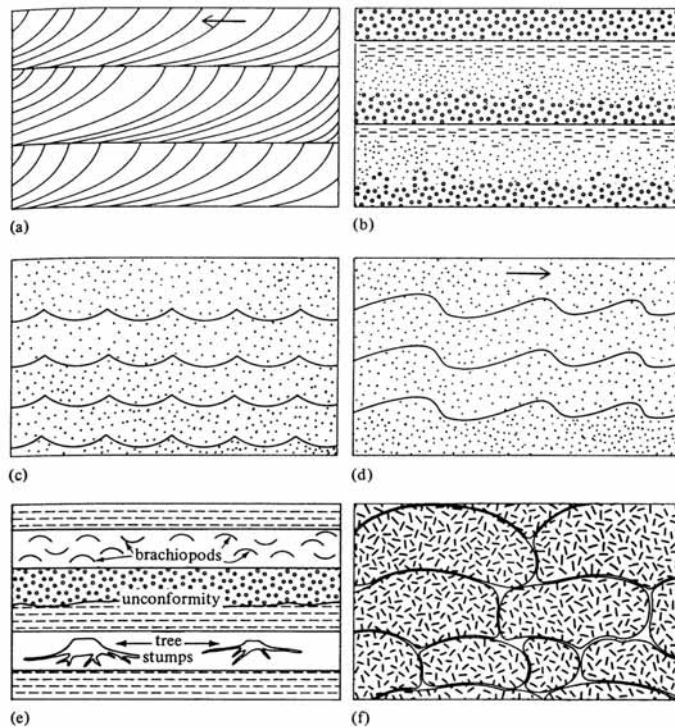

Figure 22 - Diagrammatic sketches of primary sedimentary structures used in determining topping (younging) directions in stratified rocks.

Together, these primary- and secondary sedimentary structures help the soft-rock structural geologist unravel the oft-asked field questions - namely.... Which way is up? and Which way to the package store? The direction of younging of the strata seems obvious in horizontal- or gently tilted strata using Steno's principle of superposition. But steeply tilted-, vertical-, or overturned beds can be confidently unravelled and interpreted structurally only after the true topping (stratigraphic younging) direction has been determined. As we may be able to demonstrate on this field trip, simple observations allow the card-carrying geologist to know "Which way is up" at all times.

Structures in Sedimentary- vs. Metamorphic Rocks

For hard-rock geologists working in metamorphic terranes, simple sedimentary observations will not allow the card-carrying geologist to know "Which way is up" at all. Rather, because of intense transposition and flow during ductile deformation, stratification, fossils for age dating, tops and current-direction indicators are largely useless except to identify their hosts as sedimentary protoliths. Thus, according to CM, "at the outcrop scale, metamorphism can best be viewed as the great homogenizer." Commonly during metamorphism, the increase in temperature and -pressure and presence of chemically active fluids severely alter the mineral compositions and textures of pre-existing rocks. As a result, in many instances, typical soft-rock stratigraphic- and sedimentologic analysis of metamorphic rocks is not possible.

Tectonostratigraphic Units

In metamorphic terranes, tectonostratigraphic units can best be described as large-scale tracts of land underlain by bedrock with similar age range, protolith paleoenvironment, and structure. Such terranes are generally bounded by ductile-fault zones (mylonites), surfaces of unconformity, or brittle faults. Unravelling the collisional plate-tectonic history of mountain belts is greatly facilitated by identifying former cratonic (ancient crustal), continental-margin, continental-slope-, and rise, deep-oceanic, and volcanic-island tectonostratigraphic units. The major distinction in unravelling complexly deformed mountain belts is to identify former shallow-water shelf deposits (originally deposited on continental crust) and to separate them from deep-water oceanic deposits (originally deposited on oceanic crust). The collective adjectives miogeosynclinal (for the shallow-water shelf deposits) and eugeosynclinal (for the deep-water oceanic deposits) have been applied to the products of these contrasting depositional realms.

Structural Geology of New York City

The three schist units and the underlying rocks have shared a complex structural history which involved three superposed phases of deep-seated deformation (D_1-D_3) followed by three or more episodes of open- to crenulate folding (D4-D6+). Based upon relationships found in Manhattan, CM concludes that the synmetamorphic juxtaposition of the various schist units occurred very early in their structural history.

The base of the middle schist (Є-Om) is truncated by a ductile shear zone, here informally named the St. Nicholas thrust (open symbol in Figure 16). The thrust is exposed at Inwood Hill and Isham Parks, at St. Nicholas Park, and at Mount Morris Park. The upper schist unit (Є-Oh) is in probable ductile fault contact with the middle schist unit along Cameron's Line (I-95 exposure in the Bronx) and in Manhattan. However, this conclusion is based upon regional stratigraphic evidence; in Manhattan, good exposures of Cameron's Line are rare.

Cameron's Line and the St. Nicholas thrust developed during two progressive stages of ductile deformation accompanied by isoclinal folding (F_1+F_2). The F_1 folds are inferred from a locally preserved S_1 foliation. An annealed highly laminated mylonitic texture occurs at the thrust zone (Merguerian, 1988). Recrystallized mylonitic layering formed; ribboned and locally

polygonized quartz, products of lit-par-lit granitization, and quartz veins developed parallel to the axial surfaces of F_2 folds. During D_2, a penetrative foliation (S_2) and metamorphic growth of lenses and layers of quartz and kyanite+quartz+magnetite up to 10 cm thick formed axial planar to F_2 folds which deformed the bedrock into a large-scale recumbent structure that strikes N50°W and dips 25°SW. Stereograms (Figure 23) show the distribution of 245 poles to S_2, F_2 fold axes and L_2 lineations as measured in the field (Merguerian, unpublished data).
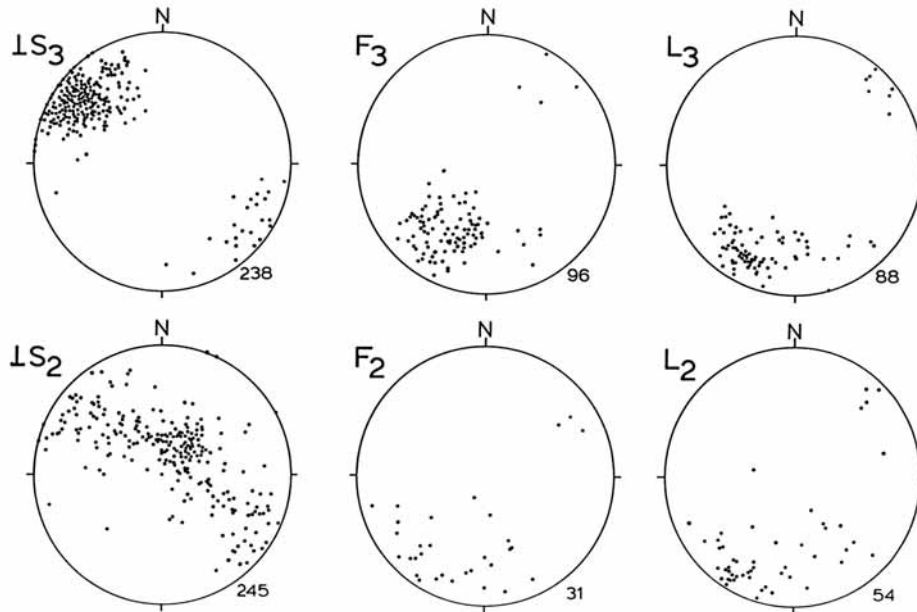

Figure 23 - Equal area stereograms showing the distribution of poles to S2 and S3, the orientation of F2 and F3 fold hingelines, and the orientation of L2 and L3 lineations. The number of plotted points indicated to the bottom right of each stereogram. (Merguerian, unpublished data).

Although the regional metamorphic grain of the New York City bedrock trends N50°W, the appearances of map contacts are regulated by F_3 isoclinal- to tight folds overturned toward the west and plunging SSE to SW at 25°. (See Figure 16.) S_3 is oriented N30°E and dips 75°SE and varies from a spaced schistosity to a transposition foliation often with shearing near F_3 hinges. The F_3 folds and related L_3 lineations mark a period of L-tectonite ductile flow that smeared the previously flattened quartz- and kyanite lenses and layers into elongate shapes. Stereograms (Figure 23) show the distribution of 238 poles to S_3, F_3 fold axes and L_3 lineations as measured in the field (Merguerian, unpublished data). Note the great-circle distribution of poles to S_2 and how the pole to that great circle corresponds to the concentration of F_3 axes.

At least three phases of crenulate- to open folds and numerous brittle faults and joints have been superimposed on the older ductile fabrics. The effects on map contacts of these late features is negligible but the scatter of poles to S3 are deemed the result of post-D_3 deformation.
Structure Sections

The localities described below offer critical evidence for new structural interpretations of the Paleozoic schists exposed in New York City. Figure 24 presents simplified W-E and N-S structure sections across the New York City area. Keyed to Figure 16, the sections illustrate the complex structural- and stratigraphic picture that CM's recent studies have enabled him to make.
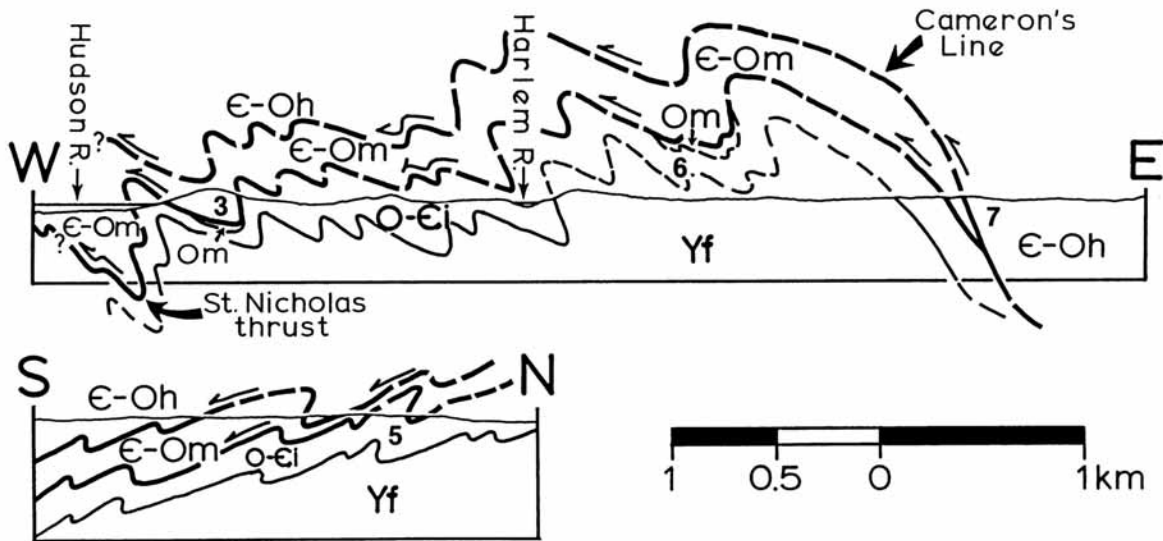

Figure 24 - Geologic cross sections across Manhattan and the Bronx showing the distribution of various tectonostratigraphic units in New York City and folded ductile faults (Cameron's Line and the St. Nicholas thrust). Symbols defined on Figure 16. (C. Merguerian, unpublished data).

The W-E sections shows the general structure of New York City and how the St. Nicholas thrust and Cameron's Line place the middle unit of the Manhattan Schist, and the Hartland Formation respectively, above the Fordham-Inwood-lower schist unit basement-cover sequence. The major F_3 folds produce digitations of the structural- and lithostratigraphic contacts that dip gently south, downward out of the page toward the viewer. The N-S section illustrates the southward plunge of lithostratigraphic units exposed in central Manhattan and the effects of the late NW-trending upright folds.

The Geology of Cameron's Line

According to Eugene Cameron (of Cameron's Line fame) in a confidential personal communication with CM, the geologic relationship of Cameron's Line was first noted by William Agar who shared them with E. Cameron. According to EC - "I don't know why they called it Cameron's Line, it should have been called Agar's Line!". In any case, Cameron's Line delimits the easternmost exposures of autochthonous Proterozoic Y and Z gneiss and overlying lower Paleozoic quartzite and marble (shallow-water sedimentary strata [Layer IIA(W)] formed originally on continental crust of proto-North America. Together, Layers I and IIA(W) represent deformed North American craton and overlying shelf deposits.

In western Connecticut, the Hartland Formation or Complex of Merguerian (1983) is interpreted as an internally sheared imbricate thrust package that marks the former site of a deep-seated accretionary complex or subduction zone. It consists of a thick sequence of interlayered muscovite schist, micaceous gneiss and granofels, amphibolite, and minor amounts of calc-silicate rock, serpentinite, and manganiferous- to ferruginous garnet-quartz granofels (coticule) (Merguerian, 1981). Hartland rocks (Unit Є-Oh in New York City) are correlative with metamorphosed eugeosynclinal (deep- water deposition) Cambrian to Ordovician rocks found along strike northward into New England (Figure 25). The allochthonous portion of the Manhattan Schist (Unit Є-Om) is directly correlative with rocks of western Connecticut and Massachusetts along the east flank of the Berkshire and Green Mountains massifs.

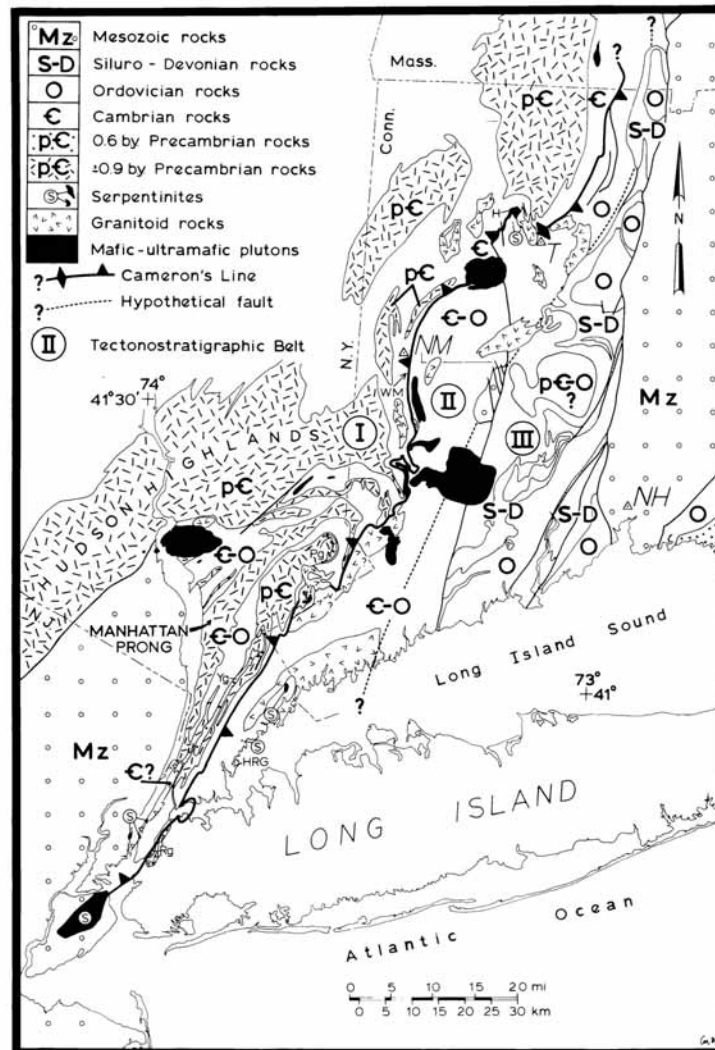**Figure 25** - Geotectonic map of New England showing Cameron's Line and the distribution of northeast-trending tectonostratigraphic units (Merguerian, 1983).

Numerous lower Paleozoic calc-alkaline plutons occur in southeastern New York and in western Connecticut. Near West Torrington, Connecticut, the Hodges mafic-ultramafic complex and the Tyler Lake Granite were sequentially intruded across Cameron's Line (Merguerian,

1977). Because of their formerly elongate shapes and because the regional metamorphic fabrics related to the development of Cameron's Line in both the bounding Waramaug and Hartland formations display contact metamorphism, these plutons are interpreted as syn-orogenic. The recognition of significant medial Ordovician plutonism across Cameron's Line (Mose, 1982; Mose and Nagel, 1982; Merguerian and others, 1984; Amenta and Mose, 1985) establishes a Taconian or possibly older age for the formation of Cameron's Line and the syntectonic development of regional metamorphic fabrics in western Connecticut (Merguerian, 1985).

Geology of Central Park

The impressive natural exposures left in Central Park by Olmstead and Vaux's Greensward Plan stand as geologic sentinels and offer a glimpse into the past. Sculpted by glacial ice during Pleistocene times, the rocky knolls record evidence of a torturous past wherein sedimentary- and volcanic protoliths were folded and metamorphosed at depths originally exceeding 20 km. Uplift and erosion have elevated these former deep-seated rocks allowing analysis and interpretation by many geologists.

CM's interest in the rocks of Central Park was spawned at an early age during visits as a child. His mineral- and rock collection still includes a garnet specimen from the park. As an undergraduate student at City College in the 1970's, he spent many hours in this splendid "geological playground" examining the mineralogic- and textural details of the metamorphic- and igneous rocks. In those days, all of the schistose metamorphic rocks of Central Park (and all of New York City, for that matter) were lumped together as the Manhattan Formation; geologists would focus on deciphering the complex fold structures. The work of Langer and Bowes (1969) first identified superposed folds in Central Park and elsewhere on Manhattan Island. While he was studying in the graduate programs at the City College and Columbia University, Merguerian's interest in the rocks of Central Park continued to develop. Thus was laid the groundwork for an enormous number of field trips run by CM for his students from these fine institutions as well as for students from the New School, Hunter College, and, starting in 1981, for students from Hofstra University. Facing the facts, CM freely admits that he would show just about anyone the rocks in Central Park at anytime. He estimates that more than five hundred individuals have shared this similar fate.

Hanley and Graff's charming book (1976) about the rocks in Central Park was not strongly focused on geologic problems but does provide include useful illustrations and descriptions of the glacial features, the orientation of cracks (joints), faults, and some details on structure in a series of outcrop sketches arranged as a walking tour through the park. Work by Nick Ratcliffe, Norm Hatch, and Rolfe Stanley in New England, by the late Leo M. Hall in southeastern New York and adjacent areas of Connecticut, and the work of many geologists from the Connecticut Geological and Natural History Survey all helped shape Merguerian's views. His subsequent Master's-thesis research was devoted to Cameron's Line and the bounding metamorphic rock units in western Connecticut. As outlined in excruciating detail earlier, Cameron's Line is interpreted as a deep-seated ductile shear zone that formed in the deep levels of a subduction complex (accretionary prism) built of materials from between the Taconian volcanic arc on the east and a lower Paleozoic continental-shelf sequence that was partially

underthrust beneath the arc massif and its continent-facing accretionary prism. (See Figure 17.) Thus, along Cameron's Line former sedimentary rocks of the continental slope and -rise (Waramaug or Hoosac formations) have been imbricated with those of deeper-water affinity (Hartland Formation). The Taconic sole thrust, mapped in New York City by CM as the St. Nicholas thrust, places former sedimentary rocks of the continental slope and -rise (Waramaug or Hoosac formations) against the filling of the Northern Appalachian Ordovician foreland basin, the Tippecanoe shales, the protoliths of the "Good Old" Manhattan Schist (and their underlying rocks, protoliths of the Inwood Marble and Fordham Gneiss).

Over the years, the rocks remain essentially the same, but ideas about the rocks change. CM's mapping experience in western Conecticut gave him a totally new perspective for reexamining the bedrock of New York City. As a result of his new studies, he was able, for the first time, to use stratigraphy and structure as the basis for a totally new interpretation. Perhaps the greatest change affected by CM involves the stratigraphic subdivision of the Manhattan Schist in its type locality as discussed earlier under the section "Bedrock Stratigraphy of New York City." Detailed work in Central Park and throughout Manhattan by CM in the 1980's indicated that three contrasting units can be recognized in what previous geologists had considered as being only a single large unit named the Manhattan Schist. Two of these three units of metamorphic rocks are present in Central Park. Both appear to be in thrust contact with underlying basal Manhattan-Inwood-Fordham basement-cover sequence. With few exceptions, the southern part of Central Park consists of rocks of the Hartland Formation (Є-Oh). North of roughly 69th Street, the metamorphic rocks are distinctly different (rocks CM has referred to as the middle unit of the Manhattan Schist - Є-Om). Rocks within the contact zone possess mylonitic fabrics related to Cameron's Line. CM's work on the rocks in Central Park has never been published; it appears in simplified form for the first time in this guidebook (Figure 26).

The complex sequence of structural events that CM has established from other parts of New York City (as described earlier) is identical to the structural sequence that can be determined in Central Park. CM mapped in detail the obvious folds in Central Park, those with steep N- to NE-trending axial surfaces and variable plunges toward the S- and SW. He found that these represent a third-generation structure (F3) that redeforms two earlier structural fabrics (S1 and S2). The older fabrics trend roughly N50°W and dip gently toward the SW (except along the limbs of F3 folds!). Based on regional correlations and isotopically dated cross-cutting igneous rocks, CM thinks all these structures are products of the Taconic orogeny. The folds- and fabrics formed during the Taconic orogeny show evidence of two- and possibly three additional fold phases that, based on their style and general lack of attendant foliations, undoubtedly took place at much-higher crustal levels than did the three Taconian fabrics. We suspect that the younger fold phases record the effects of the Acadian- and terminal-stage Appalachian orogenies.
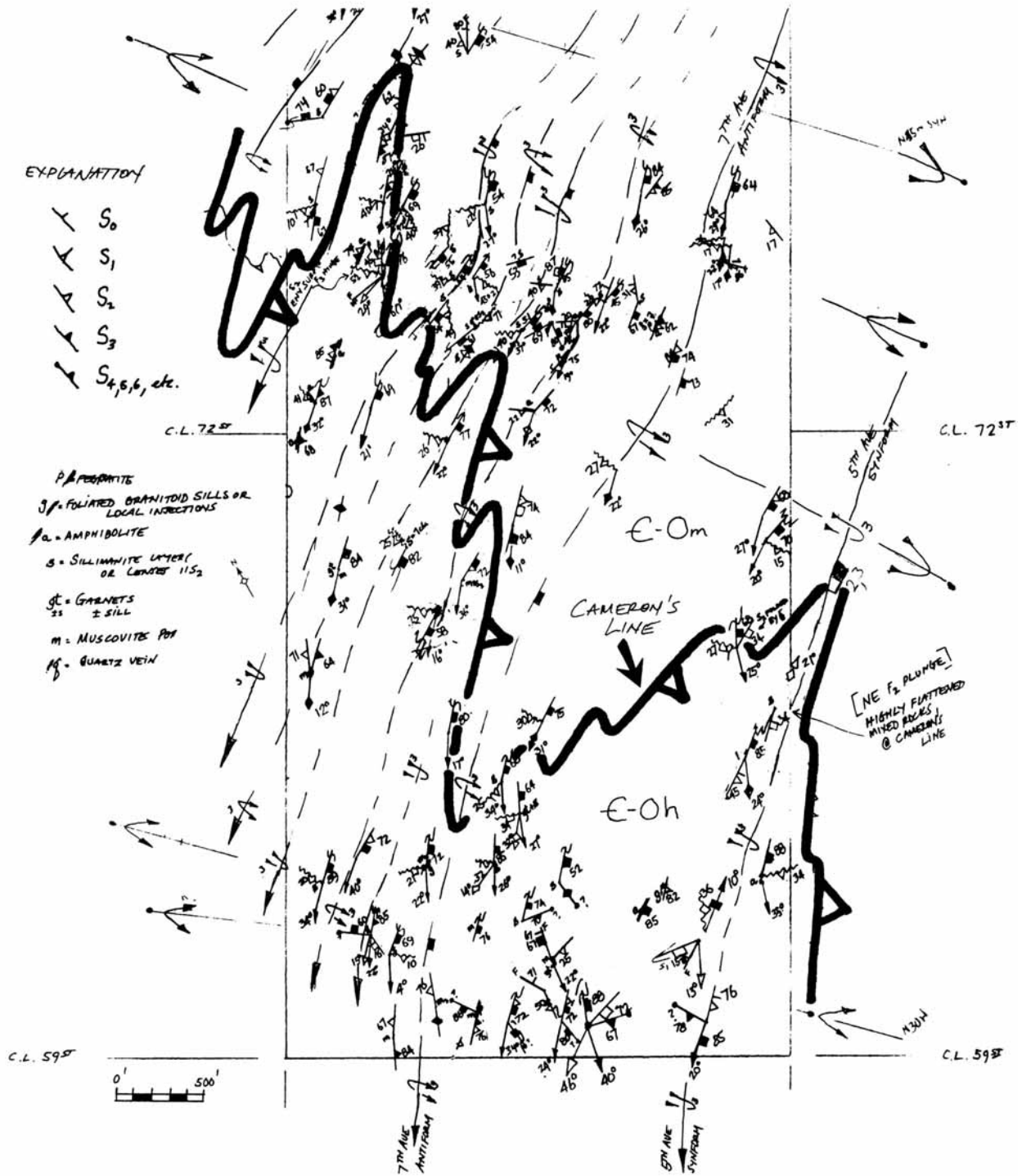
Figure 26 - Geologic map of Central Park showing the trace of Cameron's Line and axial traces of major F3 antiforms and synforms. (Merguerian, unpub. data.)

Bruce Taterka's Masters thesis (1987; carried out at the University of Massachusetts under the late Leo M. Hall and later Peter Robinson) provides excellent detailed descriptions of

various units of the Hartland and Manhattan formations. Overall, Taterka agrees with CM's interpretation of the geologic relationships, but Taterka placed the trace of Cameron's Line across an outcrop-free area of Central Park in the vicinity of the Great Lawn between 80th and 86th streets (Figure 27), well north of CM's mapped trace. Considering the degree of F1 and F2 isoclinal folding, CM suggests that Taterka's interpretation of the geometry of Cameron's Line is too simple. It is based not on the identification of ductile-fault fabrics but on differences in small-scale lithostratigraphic differences that are open to interpretation. Having spent a couple of days in the park with Bruce Taterka in both the early- and late stages of his Master's work, CM remains open to Taterka's interpretation but, as can be expected in these matters, prefers his own.

Figure 27 - Generalized map of Central Park showing subunits of the Manhattan and Hartland formations and the trace of Cameron's Line. (Taterka, 1987, p. 9.)

Baskerville's (1989) attempt to place Cameron's Line across the northern part of Central Park (Figure 28) flies in the face of twenty years of stratigraphic work. In CM's humble opinion, it is just, plain old … wrong!

Figure 28 - Geologic map of Manhattan and the Bronx showing the regional trace of Cameron's Line. I don't believe it! (Baskerville, 1989, p. 40.)

We hope that today's trip will convince participants that the absolute position of Cameron's Line is difficult to pinpoint but that in view of the superposed folds, its trace must be complex. In any case, we aim to convince you that a major Paleozoic ductile shear zone passes through southern Central Park. Of additional interest to students of Pleistocene geology are the sculpted rock surfaces within Central Park. These show evidence in support our views of

multiple glaciations in the New York City area. We describe these below under the section "Layer VII: Pleistocene Sediments" and in Table 3.

Faults and Seismicity

It is generally agreed by all geologists and seismologists that earthquakes happen as a result of sudden dislocations on faults. This means that preexisting faults tend to localize new earthquakes. The bedrock of New York City, always considered to be solid and impervious to seismic activity, is cut by a great number of ductile- and brittle faults. In addition to Cameron's Line and the St. Nicholas thrust, five northwest-trending brittle faults are indicated on CM's geologic map of Manhattan north of 125th Street (See Figure 16.) and Lobeck (1939) shows the two of the major faults of Manhattan south of the 125th Street fault (Figure 29). One of these, the famous 14th Street fault controls the lower-than-average height of buildings of the New York skyline in the area of Manhattan south of 23rd Street and north of Canal Street.
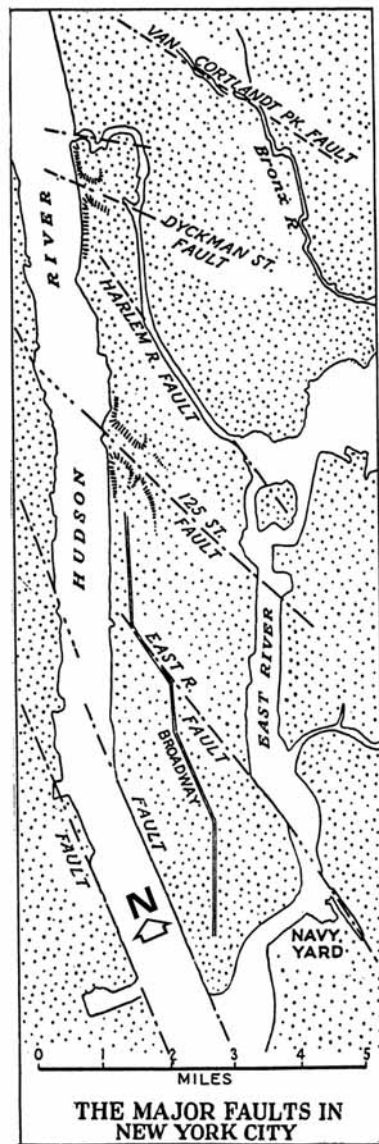

THE MAJOR FAULTS IN
NEW YORK CITY

Figure 29 - Map of Manhattan showing major faults inferred on the basis of subsurface data in water tunnels and physiographic relationships. (A. K. Lobeck, 1939.)

CM's detailed mapping in the water tunnels beneath Manhattan and the East River in the period from 1983 to 1985, has identified a multitude of brittle faults that fall into two broad categories: (1) those that trend NE-SW (parallel to the length of Manhattan) and (2) those that trend NW-SE and transect the island of Manhattan at a high angle. Invariably, where the ductile faults are oriented NE-SW, they have been reactivated by brittle faults marked by fresh clay-rich gouge up to 5 cm thick. In addition, NW-trending, steep NE-dipping faults and joints are lined with minerals such as calcite, pyrite, and zeolites. Thus, the intersection of these two important fault sets has cut New York City into a series of blocks. CM is currently preparing a new map showing the surface distribution of all ductile- and brittle faults but a finalized version was not available at press time. Copies should be available at all subway token booths and in the Mayor's office by 31 July 1999.

The Taconic Problem in New York City

The "Taconic problem" [or "problems" as we might more aptly express it to be consistent with the plural used by John Rodgers (1989) in the title of his review article: "The Taconic controversies"] refers to the geologic interpretations of the age(s) of the predominantly terrigenous and fine-textured (or pelitic) Lower Paleozoic sedimentary rocks and their metamorphosed equivalents that underlie the Taconic Range of eastern New York and of the relationships of these pelitic rocks to their neighboring rocks, many of which are likewise of Early Paleozoic age but consist of carbonate rocks. We continue by describing the Taconic range. Then follows a review some of the history of the geologic investigations.

The Taconic range (the "Taconics") designates a series of rolling hills that extend for about 240 km, from near Poughkeepsie, New York to north of Rutland, Vermont (Figure 30). At their widest point, the Taconics are 40 km across and therefore form an impressive, if not somewhat topographically subdued, physiographic province nestled east of the Devonian Catskills and Precambrian Adirondack mountains and west of the Berkshire and Green Mountain Precambrian massifs.

Based on topographic expression, the metamorphic grade of the rocks, relative structural positions, and stratigraphic relationships, the Taconics are subdivided into an eastern belt (high Taconics) and a western belt (low Taconics). The high Taconics not only reach to higher elevations, but within them, the rocks are of higher metamorphic grade, and higher structural positions than the Taconic rocks exposed farther west in the low Taconics.

Early in the history of geologic studies, during the First Geological Survey of the State of New York, in the 1830s and 1840s, a sure way to guarantee one's entry into "geologic heaven" was to propose a new geologic system. Proposals to establish two new systems within the Paleozoic were made by New York's first geologists. Ebenezer Emmons proposed the "Taconic" system for the thick body of terrigenous pelitic rocks underlying the Taconic range, and James Hall, the "New York" system, for the strata underlying the Catskills and vicinity.
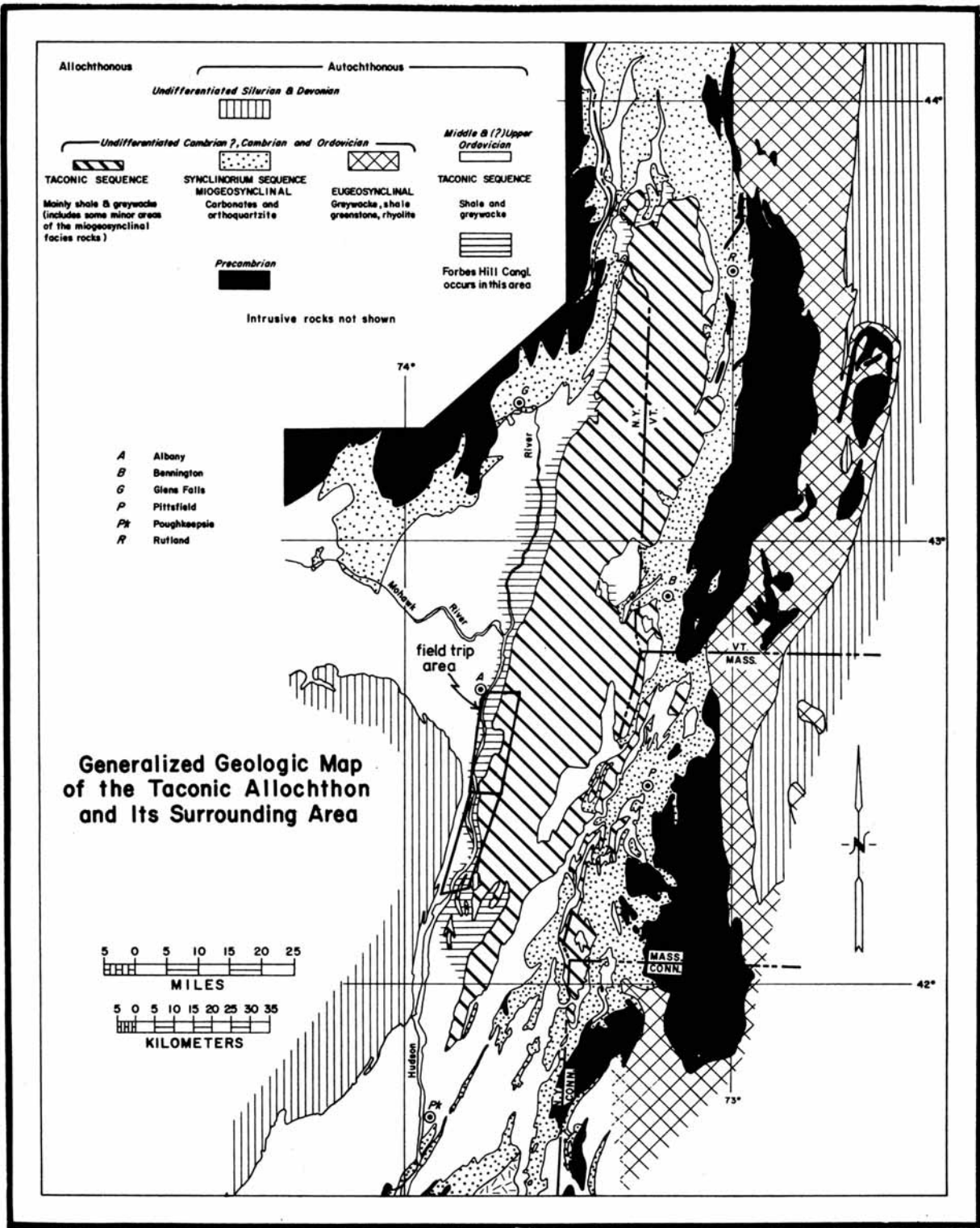
Figure 30 - Generalized geologic map of the Taconic allochthon from Bird and Dewey, 1975.

The "Taconic controvery" No. 1 centered on whether or not the rocks championed by Emmons did indeed represent strata deposited during a span of geologic time not yet identified by the European geologists who were busy naming new systems, many of which have been incorporated into the worldwide geologic time chart and thus should appropriately be accorded the exalted status of a new geologic system.

The strata within Hall's proposed "New York System" proved to be the same age as the rocks to which Sedgwick and Murchison (1838) had designated as Devonian System. Before this identity of the "New York System" and Devonian was known, Hall did everything he could to enhance the chances for having his "New York System" adopted. At the same time, he was eager to scuttle the rival Taconic System being touted by Emmons. Hall "sandbagged" Emmons at every turn, including making an incorrect identification of a key fossil found by Emmons (the only known example of such an error by New York's eminent first State Paleontologist).

The upshot of "Taconic controversy No. 1" was that the name Taconic was retained as a designation for all the terrigenous pelitic rocks, but the term was not adopted as a geologic system. Instead, the ages of the Taconic strata were found to span most of Cambrian and Early Ordovician time. Despite the efforts of its early geologists, neither of the proposed new systems based on New York rocks "made the cut."

"Taconic controversy No. 2" has pendulated back and forth and has not stopped moving. In order to explain what "Taconic controversy No. 2" is all about, we need to be specific about names and inferred ages. In our attempt to review this complex problem, it is useful to make use of terms that include large bodies of related rocks. For this purpose, we shall combine our scheme of "layers" as in Table 2 with the names of Sequences (in the sense of Sloss, 1963) as recently applied in eastern New York by Guo, Sanders, and Friedman (1990). Sloss proposed the concept of Sequences for strata underlying the North American craton that are set off from other groups of strata by a surface of unconformity of regional extent. The oldest of these he named the Sauk Sequence; it overlies the Precambrian basement and includes the carbonate rocks of our Layer IIA(W). The age range of the Sauk Sequence is from Cambrian (Early, Medial, or Late, depending on locality) through Early Ordovician. The carbonate rocks of the Sauk Sequence typically are dolomitic. Overlying the Sauk Sequence, and separated from it by a surface of unconformity of continent-wide extent is the Tippecanoe Sequence. The basal strata of the Tippecanoe Sequence are of Medial Ordovician age; they consist of limestones as contrasted with the Sauk dolostones. Above the basal limestones, the Tippecanoe Sequence consists of fine-textured pelitic rocks; these form Layer IIB of our Table 2.

The Taconic Sequence [Layer IIA(E) of Table 2] designates the terrigenous pelitic rocks the lower part of which are the same age as the carbonate rocks of the Sauk Sequence (Early Cambrian to Early Ordovician). Terrigenous pelitic rocks of the Taconic Squence were found in structural positions above the Sauk Sequence carbonates. Such an arrangement is the basis for the interpretation that a large Taconic overthrust had displaced the Taconic strata westward on the order of 100 km or more. (See summary in Kay, 1937.) The displaced Taconic strata were thus considered to constitute a vast allochthon.

Complications have arisen over the age span of the upper part of the Taconic Sequence. The issue is whether or not the upper part of the Taconic Squence spans the same range as the lower part of the Tippecanoe Sequence (Medial Ordovician).

Further understanding requires the reader to become familiar with some of the names of the subdivisions of the Middle Ordovician limestones of the lower part of the Tippecanoe Sequence and of some graptolite zones.

Early in the twentieth century, the Middle Ordovician limestones of the lower Tippecanoe Sequence in New York State were organized as follows:

                    Trenton

  Middle Ordovician   Black River (Lowville Limestone in U. pt.)

                    Chazyan

The key graptolites belong to a distinctive fauna associated with the genus Nemagraptus. The pendulating problem is the correct age of this diagnostic Nemagraptus fauna. In New York, the Nemagraptus fauna was found in the Normanskill Shale; in Tennessee, this fauna characterizes the Athens Shale. The issue is not whether the Normanskill correlates with the Athens Shale, but rather how to fit both the Normanskill and the Athens into a correct time-stratigraphic scheme. Wherever one of these formations is assigned, the other has to go with it.

The way to determine the correct position of a particular faunal zone is to study stratigraphic successions that are as complete as possible and to analyze the distribution within these successions of the contained fossil assemblages. As far as graptolites go, a long-standing tendency has existed for American paleontologists to assign particular graptolites to a higher stratigraphic position than British- and Canadian specialists tend to do. A further way to check on the age assignments is to compare information obtained from strata containing graptolites (usually dark-colored shales) with that obtained from strata containing other fossils, for example brachiopods and trilobites in the limestones.

The age of the Normanskill Formation lies at the heart of the pendulating "Taconic controversy No. 2." JES would go so far as to contend that on the first swing of the pendulum, the initial controversy over the correct age of the Normanskill delayed any rational understanding of the Taconic strata for more than fifty years. We are now in the midst of the second swing of the pendulum. JES wonders if another 50 years will elapse before the matter is resolved.

The first swing of the pendulum involved a careful- and comprehensive paleontological effort not likely to be duplicated ever again. The individual who carried out this great effort was Rudolf Ruedemann. Early in his studies of the Normanskill Formation, Ruedemann found the

distinctive Nemagraptus fauna. Intercalated within the Normanskill Formation, Ruedemann found a peculiar formation that he named the Rysedorph Hill Conglomerate.

The Rysedorph Hill Conglomerate contains fossiliferous limestone pebbles. Ruedemann collected a wagon load of these pebbles, took them to his house and broke them apart in search of fossils. To do this, he would heat the pebbles in the oven of his kitchen stove and then take a pair of tongs and plunge the hot pebbles into a bucket of cold water. The pebbles would break along any fossils within.   Some of these pebbles contained Early Trentonian fossils. Given such fossiliferous pebbles, Ruedemann (1901b) concluded that the age of the Normanskill must be post-Early Trentonian. Indeed, he inferred that the age of the Normanskill fauna is Late Trentonian (in the older sense shown above; not Late Trentonian of G. A. Cooper, 1956). On the face of it, one would think that Ruedemann's results would have settled all questions about the stratigraphic age of the Normanskill Formation and the Nemagraptus fauna.

However, things were not that simple. And why? Because one of Ruedemann's contemporaries was a crusty character named E. O. Ulrich. Mr. Ulrich was a powerful individual and he thought that he understood the stratigraphic relationships of the Ordovician strata in northeast Tennessee beyond any shadow of doubt. There, the Athens Shale underlies a distinctive fine-textured limestone that looked just like the Lowville Limestone of New York (part of the Black River subdivision in table above). Indeed, this post-Athens-Shale limestone in Tennessee had been given the name Lowville. Most workers were happy both with this extension of a New York name into Tennessee and the interpretation that accompanied it, namely, that the formation was the same age as the New York Lowville. Therefore, whatever underlay the Lowville had to be of Chazyan age. Accordingly, Ulrich was convinced that the correct age of the Nemagraptus fauna of the Athens Shale of Tennessee (and also the Normanskill of New York) was Chazyan. In the face of Ruedemann's new data about the Early Trentonian age of the Nemagraptus fauna, one might have supposed that Ulrich would have reevaluated his faith in the Lowville Limestone situation. (As it later worked out, Cooper and Cooper in 1946 showed that the limestone in Tennessee is much younger than Ulrich thought, i.e., it is a correlative of the New York Trenton, not the New York Lowville.) But, Ulrich was Ulrich, and he thundered down on poor Ruedemann. Ulrich's message: THE NORMANSKILL IS CHAZYAN--period, exclamation point!

As long as the terrigenous Normanskill strata were assigned a Chazyan age, then the Normanskill had to be considered as belonging to the Taconic Sequence and thus to be a part of the Taconic allochthon (i. e., terrigenous strata same age as and above the carbonates). By contrast, if the age of the Normanskill initially assigned by Ruedemann and supported by W. B. N. Berry (1960, 1962, 1963, 1973) (i.e., post-Lower Trenton) is considered to be correct, then the Normanskill belongs to the Tippecanoe Sequence. Accordingly, its position above carbonates need not involve the Taconic allochthon. Instead, Trentonian-age Normanskill beds are parts of the autochthonous terrigenous strata that unconformably overlie the basal limestones of the Tippecanoe Sequence--they are part of the filling sediments of the Northern Appalachian Ordovician foreland basin. Indeed, Berry's reaffirmation of Ruedemann's initial Trentonian age assignment of the Normanskill formed the basis of what was thought to be the "solution" to the "Taconic problem" (Zen, 1961, 1963, 1967; Sanders, Platt, and Powers, 1961; Platt 1962; Theokritoff, 1964).

In the face of Ulrich's dogmatic assertion, Ruedemann actually abandoned his original correct assignment of the age of the Normanskill as Late Trentonian. Every time Ruedemann wrote about this, he would quote Mr. Ulrich as "authority" for a Chazyan assignment. As a result, much of Ruedemann's geologic mapping turned out to be wrong. Everywhere he showed the supposedly Chazyan-age Normanskill, he had to map an overthrust at its base where it was in contact with the Cambro-Ordovician carbonates (whose topmost unit was the Lower Trenton Limestone).

One can only wonder at what private thoughts must have been dancing around inside Rudolf Ruedemann's head each time he was forced to "knuckle under" in print to Ulrich by reciting that Mr. Ulrich said the age of the Normanskill is Chazyan. Perhaps Ruedemann soothed his conscience by including his persistent disclaimers that the Normanskill might be as young as "Black River." (Ruedemann was thus trying to bring the Normanskill up in the column where he thought it belonged, but did not want to get Mr. Ulrich's back up by going as high as Trenton.)

How much farther along New York stratigraphy and -structure would have been if Ruedemann had been a more-combative individual. Scientific progress would have been greatly served had Ruedemann stood up on his hind legs on the age of the Normanskill and told E. O. Ulrich to go right straight to hell on this matter (and could have made that remark stick). As it was, Ruedemann lacked the courage of his correct scientific conviction, and the whole subject was a mess until W. B. N. Berry straightened it out in the 1960's.

[Because of the likelihood that large-scale overthrusts took place in the Hudson Valley region during the Late Paleozoic deformation, it needs to be emphasized that an authochthonous structural position with respect to the Late Ordovician deformation does not preclude an allochthonous position during the Late Paleozoic deformation.]

In 1973, the pendulum took another swing. Following the graptolite zonation advocated by Jean Riva (a Canadian; note Ruedemann's comment above about the "Empire" paleontologists' propensity with respect to the age assignments of graptolites), Rickard and Fisher (1973) published a paper advocating a "born-again" Chazyan age assignment for the Normanskill. It would be one thing if they had just published such a paper. Despite W. B. N. Berry's written comment that no basis existed for the Rickard and Fisher correlations, these two, being firmly entrenched in the New York State Geological Survey in Albany, were able to incorporate their disputed interpretation about the Chazyan age of the Normanskill into the second edition of the New York State geologic map. On this map, the strata in all localities previously mapped as Normanskill are indicated as belonging to the Taconic allochthon. In JES's opinion, this 1970 New York State geologic map incorporates all the errors of Ruedemann's mapping based on E. O. Ulrich's fiat about the Chazyan age of the Normanskill.

In the remainder of this discussion about how the status of the Taconic controversy affects the geologic relationships in New York City, we shall proceed on the proposition that the 1901 Ruedemann view as reinforced by W. N. B. Berry and others is correct. In other words, for the age of the Normanskill, we vote Trentonian; we totally reject the Ulrich-Riva-Rickard-

Fisher-and anybody else's Chazyan assignment. As far as the rocks go, this means that in any region along the former passive continental margin which later experienced the conversion to a convergent margin, the following predictable relationships exist. At the bottom, basement. Above this, the Sauk Sequence, in eastern areas, beginning with Lower Cambrian. In the Sauk Sequence, dolomitic carbonates prevail (at least in areas closest to the former continental interior), but quartz sandstones are present at the base and at many levels higher up.

Above the regional surface of unconformity at the top of the Sauk Sequence are the limestones of the basal Tippecanoe Sequence. Collectively, the entire Sauk Sequence and the basal Tippecanoe limestones are the Cambro-Ordovician carbonates [our Layer IIA(W)]. Then comes another surface of unconformity along which more karst features formed; the shallow sea floor emerged and was subjected to the effects of rainfall and subaerial exposure. Then, the "plug" literally was "pulled." A foreland basin formed and subsided by thousands of meters in a very short time (geologically speaking). Deep-water terrigenous sediments, the Normanskill and equivalents, were deposited unconformably above the limestones. Such terrigenous sediments above carbonates resulted from rapid subsidence and -deposition. These terrigenous sediments were not overthrust into their positions above the carbonates; they are younger than the carbonates. But, overthrusting is but a stone's throw (in time) away. While these Normanskill terrigenous strata were being deposited, the Taconic allochthon moved into high gear. The older terrigenous strata, namely the Taconic Sequence, whose age extends back to the Early Cambrian from whatever point within the Medial Ordovician the allochthon set forth upward and westward, plowed across the sea floor of the foreland basin.

Now, in a position structurally above the carbonates, the displaced older terrigenous pelitic strata [Taconic Sequence, our Layer IIA(E)] were "merged" with in-situ younger terrigenous strata (Normanskill part of the Tippecanoe Sequence, our Layer IIB). The result is a great body of terrigenous strata above a great body of carbonates. After the whole has been subjected to regional metamorhism, the result is marble below and schists above. As a first approximation, one would suppose that all the schists are younger than the marble. This is exactly the interpretation formulated by the Merrill and his colleagues when they proposed the name Inwood Marble and Manhattan Schist. But, if the marble and the schists are metamorphosed rocks that are part of the "Taconic problem," then structurally above the marbles are two categories of schists: (1) those whose protoliths were deposited in the Ordovician foreland basin as part of the Tippecanoe Sequence (Normanskill; our Layer IIB), which are younger than the marble; and (2) those whose protoliths were transported there as part of the Taconic allochthon [the Taconic Sequence, our Layer IIA(E)], whose age span is virtually the same as that of the marbles (exactly so for the bulk of the Taconic Sequence, but allowing for some to be younger at the top, namely whatever material kept on accumulating in the deep basin while the carbonates to the west were being eroded and while some parts of the Normanskill were being deposited in the foreland basin).

In the CM view of things, the "good old Manhattan Schist" is the metamorphosed equivalent of the foreland-basin-filling Normanskill strata (i. e., that part whose protoliths were truly in situ, belong to the Tippecanoe Sequence, and were deposited unconformably above the basal Tippecanoe limestones), whereas the "bad new Manhattan Schist" is the metamorphosed equivalent of two parts of the Taconic Sequence (= Waramaug and Hartland formations), whose

protoliths are basically the same age as the Inwood Marble and owe their structural positions above the marble (and also above the "good old Manhattan Schist") to displacement along two great overthrusts, the St. Nicholas thrust below, and the Cameron's Line thrust above. (See Figures 16 and 24.)

How to sort all this out depends on how one feels about the term "Manhattan Schist." If one adopts the view that the only appropriate basis for continuing to use "Manhattan Schist" is as implied in the original definition, i. e., schists younger than the Inwood Marble, then only CM's "good old Manhattan Schist" merits the designation of "Manhattan Schist." By contrast, if one adheres to the view that all the schists on Manhattan Island are what belong under the term "Manhattan Schist," then continued use of the term "Manhattan" merely serves to perpetuate confusion about the correct ages- and structural relationships of the schists. Accordingly, the term "Manhattan Schist" should be discontinued and totally replaced by three other names: one for the in-situ Normanskill-age (post-marble) schists and two others, for the overthrust marble-age schists. You pays your money, and you takes your choice.

The Taconic Orogeny

The late Medial Ordovician orogenic events are collectively designated as the Taconic Orogeny. Formed during this orogenic episode were the Taconic overthrusts (as already mentioned). At the same time, and somewhat earlier, an extensive fold belt, a zone of regional metamorphism, and various plutons dated at roughly 460-400 Ma were intruded. (See Table 1.) As mentioned, while the deep-water turbidites and related sediments of the Tippecanoe Sequence were accumulating, the Taconic allochthon was emplaced, with much of the thrust plate moving along the sea floor of the Northern Appalachian foreland basin. To many geologists, subscribing to the older thinking (Zen, 1967; Bird and Dewey, 1975; Ratcliffe and others, 1975) (Figure 35) the Taconic orogeny was envisioned as a series of gravity-induced slides (the Low Taconics) and eventually overthrusts (the High Taconics) of the oceanic sequence [Layer IIA(E)] above the Appalachian carbonate platform [Layer IIA(W)] and overlying flysch [Layer IIB]. This episode of continentward displacement was driven by the encroachment of a volcanic arc (the Ammonoosuc-Oliverian Complex in Figure 17) against the passive continental margin of Ordovician North America.

Many modern workers [including CM, JES, Rowley and Kidd (1981), Stanley and Ratcliffe (1985)] do not believe in gravity sliding as a model for the emplacement of the structurally lowest Taconic allochthons. Rather, based on stratigraphic- and structural evidence, these workers envision all Taconic displacements as being the result of continentward overthrusting of a subduction complex formed between the oceanward-facing continental margin sequence and the encroaching Taconic arc. (See Figure 17.) The main argument for gravity-induced sliding of allochthons, the presence of olistostromes and wildflysch conglomerates on the western, leading edge of the Taconic allochthon, are now interpreted as deposits of forethrust olistostromes in front of overthrusts that advanced westward across the floor of the Northern Appalachian Ordovician foreland basin. As far as is now known, the Taconic allochthon itself includes only sedimentary strata; no pre-Taconic continental basement has been found. However, such massive overthrusts of strata over strata may be accompanied by thrust slices in

which the basement overrides sedimentary strata. In eastern New York State, Zen and Ratcliffe (1966) and Ratcliffe and others (1975) have mapped and identified overthrust slices of Cambro-Ordovician carbonates beneath the Taconic sole thrusts.

In Newfoundland, thick slices of oceanic lithosphere (i.e., an ophiolite succession) have been thrust over the Cambro-Ordovician shallow-water platform carbonates. Detrital chromite, a mantle-derived chromium oxide, probably shed westward during subaerial exposure of ophiolitic slabs, has been found in the foreland-basin flysch deposits associated with the Newfoundland "Taconics". In Dutchess and Orange counties, New York, mid-Ordovician overthrusts beneath the Taconian overthrusts transported granitic basement westward above the sedimentary strata. In many localities, subsequent erosion completely removed any and all such slice(s) of granitic basement on the overthrust block. This possibility is mentioned here because an overthrust block composed of granitic basement rocks could have provided a supply of coarse quartz to form the Lower Silurian Green Pond-Shawangunk-Tuscarora-Clinch sheet of sandstones and local conglomerates at the base of Layer III. Alternatively, the thick quartzose deposits could have been formed from reworked bull quartz veins found along the Taconic thrust faults (JES thinks this is a lot of bull, quartz!), or from eroded pegmatites associated with the roots of the Taconic volcanic arc. The parent deposit of all this Silurian-age quartz is, as yet, a mystery.

Similar to the relationships noted in the Antler orogenic belt of California and Nevada, the deep-seated Taconian folding, metamorphism, and igneous activity occurred shortly before the Taconic allochthon had been emplaced (Merguerian, 1985b). Available age data indicate that the compressive ductile deformation in the igneous- and metamorphic root zone of the Taconic orogen led the supracrustal emplacement of overthrust sheets by a minimum of 20 Ma. The polydeformed internal massifs presumably mark the deep levels of continentward-facing accretionary complexes within which deep subduction and deformation of oceanic deposits preceded the collision of the encroaching volcanic-arc terranes. Final docking of the arc resulted in cratonward thrusting of the shallow levels of the subduction complex to form the Taconic allochthon. As such, we see a time gap in deep-seated- versus supracrustal deformation, wherein a geometrically predictable vertical pattern of diachroneity within subduction complexes in collisional orogens occurs.

Post-Taconic Crustal Disturbances

Following the Taconic orogeny, the rocks of southeastern New York were effected by man Paleozoic mountain-building disturbances that involved folding, metamorphism, and faulting (both high- and low angle). As summarized on Tables 1 and 2, the Acadian orogeny of Devonian age produced folds; rocks were deeply buried and regionally metamorphosed; and the Peekskill Granite as well as other granites were intruded. In addition, in the rocks of Layer III, the Acadian orogeny produced high-angle reverse faults and possibly low-angle thrusts. After the Acadian orogeny, southeastern New York underwent an episode of continued uplift and erosion. In the Permian Period, however the terminal phase of the Appalachian orogeny occurred. (Some geologists, wishing to downplay the concept that the Paleozoic Era was brought to a close by a majestic Appalachian orogeny, propose to trivialize, even abandon the term Appalachian, and in its place, to establish the "Alleghanian.") The effects of the Late

Paleozoic orogeny are best observed in the southern Appalachians and in Rhode Island where rocks of late Paleozoic ages have been folded, faulted, intruded, and metamorphosed. In these widely separated areas, low-angle overthrusts involving basement, and coincident folding of sedimentary cover rocks is well documented. In addition, coal in Pennsylvanian-age strata in Rhode Island has been raised to the rank of graphite and in eastern Connecticut, granites were intruded.

Armchair geologists (or plate pushers) conjecture that the Acadian orogeny was driven by continentward subduction of ocean crust to the oceanward side of the Taconian arc-continent collision zone. Thus, the Acadian orogeny, basically a brief, thermal event, could be visualized as the result of Andean-type subduction. Following a period of strike-slip displacement of geologic terranes, the "big one", as Fred Sanford would say, occurred. The Appalachian orogeny is thought to have been the result of a continent-continent collision between North America and Africa to close out the Paleozoic Era. Deep seismic- reflection profiles across the southern Appalachians demonstrate the significance of low-angle overthrusts of crystalline basement rock. In some cases, layered reflectors (probably Paleozoic sedimentary strata), are found beneath the huge overthrust sheets. Clearly, the effects of Late Paleozoic low-angle thrusting cannot be discounted in southeastern New York just because the post-Devonian strata were here eroded (or not deposited).

There are obviously many post-Taconic events to explain the multitude of folds and low- to high-angle faults found to affect Taconic rocks throughout southeastern New York. In addition to these of Paleozoic age, remember (Table 1) that during the Triassic and Jurassic, North America and Africa split apart again with renewed normal- and strike-slip faulting. Commonly, the rejuvenation of plate motions reactivates pre-existing weak zones in the Earth's crust. Thus, it is not uncommon to find faults with complex, movement histories that may, in fact, record protracted Taconic-, Acadian-, Appalachian-, as well as Newarkian tectonic activity. In the field, we shall attempt to identify and discuss these post-Taconic structures and develop the idea that high-angle faulting and block uplifts (horsts) and downwarps (grabens) can cause abrupt changes in lithology and metamorphic grade. Steep metamorphic gradients, truncated low-angle thrust faults, and rapid lithologic variations may be the result of such faulting.

Plate-tectonic Interpretation

During Early Paleozoic time, the present eastern seaboard of North America formed a broad continental margin with a broad oceanward-facing shelf similar to today. The early Paleozoic shelf received clastic products of the weathering and erosion of the exposed Proterozoic continental crust and carbonate sediments that accumulated on a shallow sea floor in a near-equatorial warm water environment (Figure 31). Thus, a continental terrane was formed with a basal layer of Proterozoic granitoid rocks (Fordham protolith) unconformably overlain by discontinuous sand, lime, and clay (Lowerre, Inwood, "Good Old" Manhattan Schist protoliths). Outboard of the shelf edge, on quasi-continental "transitional" crust, a sequence of poorly bedded silt and turbidites formed (protoliths of the middle unit of the Manhattan Schist - Є-Om, the Waramaug Formation). In the deeper oceanic environment, deep-water shale, a few

turbidites, and intercalated volcanic rock accumulated on oceanic crust in the vicinity of a volcanic archipeligo (protoliths of the Hartland Formation - C̶-Oh). (See Figure 13.)

Figure 31 - Paleogeographic map of North America in Early Paleozoic time. (Kay, 1951).

During the Medial Ordovician Taconic orogeny, as a result of arc-ward subduction, the Taconic volcanic arc collided with, and was accreted to the North American shelf edge, which was a part of the former passive continental margin of ancestral North America. Deformation- and metamorphism of the bedrock units of New York City took place deep within a trench beneath the Taconic arc with internal telescoping of the continental shelf, slope/rise, and oceanic realms along arcward-dipping shear zones within a deep-seated subduction complex. Development of the St. Nicholas and Cameron's Line thrust faults accompanied closure of the marginal ocean basin separating the Taconic arc from the mainland. The bedrock geology of southeastern New York and western Connecticut preserves this collisional boundary in a series of subvertical, NE-trending, fault-bounded lithotectonic belts. (See Figure 25.) Belt I is

bounded on the east by Cameron's Line and marks the Continental Terrane. Locally, within Belt I are allochthonous rocks of the slope/rise sequence. Belt II is the Hartland Terrane of deep-water oceanic deposits and Belt III consists of the roots of the Taconic volcanic arc which also crops out to the east of the Connecticut River valley basin and extend through central Massachusetts into New Hampshire.

LAYER VII: QUATERNARY SEDIMENTS AND ASSOCIATED FEATURES ERODED BY GLACIERS ON BEDROCK SURFACES

Under this heading we include: (1) features of Pleistocene age (related to former continental glaciers) and (2) features (mostly sediments) of Holocene age that resulted from the Flandrian submergence, which took place as the continental glaciers disappeared.

Features of Pleistocene Age

Features of Pleistocene age are distinguished by their associations with the several continental glaciers that formerly flowed across the region. These glaciers eroded the bedrock, transported various erratics to new locations, and deposited blankets of sediment. These sediments consist of sheets of till and various bodies of outwash that were deposited when the glaciers melted. As veteran On-The-Rockers are well aware, JES and CM (the two chief "Off-Their-Rockers") have entered the debates about the glacial history of the New York region, initially by finding hitherto ignored- or not-noticed features of glacial erosion and/or indicator erratics. Such features have provided them with new insights into the stratigraphic relationships displayed by the Pleistocene sediments. Moreover, their studies of the Pleistocene sediments are now providing feedback into their continuing investigations into glacial sculpting of the bedrock. All their new information totally destroys the prevailing "one-glacier-did-it-all" concept that seems to have hypnotized most modern stratigraphers of the Pleistocene deposits. The "one-glacier" interpretation further specifies that the glacial features made in the New York metropolitan region are not only the work of a single glacier but that this glacier should be correlated with the Woodfordian episode (interval from about 20 ka to 13 ka, namely the most-recent general ice advance) and furthermore that this Woodfordian glacier flowed down to New York City from the Labrador highlands following an azimuth that is about N15°E to S15°W (a direction that is down the Hudson-Hackensack lowlands). JES and CM find that only a few local glacial features can be ascribed to the effects of the Woodfordian ice. Instead, they find numerous features that can be ascribed only to several older glaciers. Some of these older glaciers must have flowed from NNE to SSW (as did the Woodfordian ice), but many flowed from various azimuths in the NW quadrant toward the SE, across the Hudson Valley. We review briefly the features made by glacial erosion, summarize some data from indicator stones, and then discuss the Pleistocene sediments.

Features Made by Glacial Erosion of Bedrock

Features eroded by glaciers in bedrock include striae and grooves, crescentic marks, roche moutonnées, and rock drumlins. All are useful in determining one of the most-fundamental points about a former glacial, namely which way did the glacier flow?

Striae and Grooves

In flowing over certain kinds of solid bedrock, a glacier may create a generally smooth, possibly rounded surface on which may be linear scratches (striae, erroneously referred to as "striations" by many geologists whose use of the English language is in such a state of disarray that they do not bother to distinguish between words for attributes and words for substantive things) and even large grooves. The linear scratches and -grooves provide a straightforward basis for inferring ice-flow direction: it is parallel the trend of the linear grooves, -striae, and other elongate features.

Such delicate marks as striae do not survive exposure to the atmosphere for more than a few decades or so. Examples that can be used for showing the rate of destruction of the marks come from Finland, where postglacial crustal elevation has caused many islands to emerge from beneath the water of the Baltic Sea. The water has removed the fines from the till, leaving behind a glaciated rock pavement on which rest various large erratics. Not many striae have survived for longer than a century.

In a study of glacial striae cut into the bedrock by the Saskatchewan Glacier in Alberta, Iverson (1991) illustrated examples of three categories: (a) groove widening in a down-flow direction and ending abruptly in a deepened part against a slope that dips steeply in an up-flow direction; (b) groove symmetrical and ending at sharp points at both ends with deepest excavation at midpoint; and (c) groove widest at up-flow end [a near-mirror image of those of group (a)]; long profile asymmetric, beginning at a steep slope, dipping in a down-flow direction, and dying out at the pointed down-flow end. He also carried out experiments in which blocks of carbonate rock were forced against a fixed striator point having various shapes.

L. D. Gale's study of "Diluvial scratches and furrows: carried out in 1828-1829. The first systematic attempt to record directions of striae and grooves on the bedrock in New York City, was carried out in 1828-29 by L. D. Gale (Mather, 1843). At that time, most of the present-day streets had been laid out, but only a few buildings existed north of what is now known as Lower Manhattan. Therefore, Gale's street references can be taken directly, but one has to realize that either no buildings were present, or the ones to which he does refer have probably been long removed.

As was common in his day, Gale supposed that the grooves and scratches had been made by water currents, perhaps assisted by icebergs. The presumed significance of water is implied in the use of the term diluvial.   The following paragraphs are quoted from L. D. Gale (1839, Geological Report of New-York; New-York island; in Mather, 1843, p. 209-210):

"Diluvial grooves and scratches have been found in
every section of the island, from Sixteenth-street
on the south, to 200th-street on the north, (or to

the southern termination of the limestone;) and from the banks of the Hudson on the west, to Harlem river on the east. The furrows generally are most distinct where the rock has been recently uncovered, and least where it has been long exposed to the action of the elements. They have been found on the highest rocks, and at the lowest tide-water marks, being a difference of more than one hundred feet perpendicular height. The furrows are always most strongly marked on the northwestern slopes of the hills, and least so on the southeastern. In many instances they are very distinct on the western (sic) and northwestern slopes, extending to the highest point of the rock; but no traces are to be seen on the eastern (sic) and southeastern slopes, although both slopes are equally exposed.

"Direction of the furrows. Observations of the diluvial furrows were made in between sixty and seventy different places on the island. Taking together the whole series of observations, the general course of the current was from northwest to southeast, or north forty-five degrees west, but varied in the extremes from north twenty-five degrees west to north forty-eight west, making a difference of twenty-three degrees. Of the whole series of observations, thirty-nine were north forty-five degrees west, twelve varied from north forty-five degrees west (seven being north thirty-five degrees west), two were north forty-eight degrees west, and a few scattering ones varying from north thirty-five degrees west to north forty-five degrees west.

"Abundance of the furrows. The furrows occur most abundantly in the middle portions of the island, between the city and the Harlem and Manhattanville valley, somewhat less in the western, and least of all in the eastern.

"Direction of the furrows in particular neighborhoods. 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. About one fourth of all are on the west side,

and vary but little from north thirty-five degrees west; and about one-eighth on the eastern side, where the direction varies from north twenty-five degrees west to north thirty-five degrees west. In connection with this subject, I have examined the surface of the greenstone on the neighboring shores of New-Jersey (sic), and find their grooves and scratches abundant, and their general direc-/ (p. 210): tion is north forty-five degrees west. Hence it appears, that the diluvial current which once swept over this island from northwest to southeast, on reaching the western shore, was deflected southward, as by the action of some force at a right or some other angle to its course; and that the same current, before it reached the middle of the island, again assumed a southeasterly direction, but was again diverted southerly on approaching the eastern shore. That some portion of the current was diverted southerly on reaching the western shore of the island, is evident, not only from the diluvial furrows, but from the boulders of anthophyllite found in large numbers in the lower part of the Eighth avenue near Fifteenth-street, a distance of two miles in a south-southwest direction from the only locality whence they could have proceeded. Again, the white limestone of Kingsbridge has been distributed along the eastern shore of the island, in a direction almost due south of the only locality in the vicinity where it is found in place; whereas had they been carried in the general direction of the current, they would have been deposited eastward in Westchester county, as before stated.

"Magnitude of the furrows. The size of the furrows varies in the same and different localities. Sometimes they are the finest scratches, not more than a line in diameter horizontally, and of the smallest appreciable depth; from this they increase to grooves four inches deep and eighteen inches in horizontal diameter. In a few cases, they are furrows, or rather troughs, more than two feet wide and six or eight inches deep. A case of the latter kind occurs on Eighth avenue, between Seventy-ninth and Eight-first-streets; and one of the former on the west side of the island, on the very banks of the Hudson,

five hundred yards north of Mr. John H. Howland's
country seat (near Ninety-seventh-street).

"Convenient places for examining the diluvial
furrows. The nearest places to the city for
examining the furrows are at the junction of Twenty-
second-street and First avenue, south of the Almshouse
yard; and again about half a mile northward at Kip's
bay, at the junction of First avenue and Thirty-fifth-
street. Both of these localities will soon be
destroyed by grading the streets. Some of the most
interesting localities have been made known by cutting
through Eighth avenue, from Bloomingdale road, at or
near Sixtieth-street, to Harlem and Manhattanville
valley at 105th-street; these locations are on both
sides of the avenue, and very conspicuous. Another,
equally interesting in many respects, is on the banks
of the Hudson west of the Bloomingdale road, about
six miles from the city, and about six hundred yards
northwest of Burnham's hotel. The interest excited
by this locality arises from the fact, that the
furrows ascend from beneath the lowest tide water,
up to an elevation of seventy feet in three hundred
or four hundred feet distance." (Gale, 1839, p. 197, 199.)

Gale's observations clearly suggest the effects of two contrasting flow directions, (a)
nearly all the "diluvial scratches and furrows" indicating flow from the NW to the SE and (b) the
displacement of indicator erratics (the anthophyllite-bearing rock and the white limestone)
showing transport from the NNE to the SSW. Yet his interpretation of his data was that of a
single event, which he expressed as "the diluvial current." Gale tried to show how the changes
in flow of a single such current could account for both the regional trends of the scratches and
furrows on the smoothed bedrock and the displaced indicator erratics. In this regard, Gale began
a pattern that would be followed by most subsequent students of the "diluvial" deposits: trying
to account for all the disparate observations by invoking only a single transport event. But
Gale's single transport event differed significantly from the one favored by later investigators.
Gale concluded that his single "diluvial current" had flowed from NW to SE and he sought
aberrations in this flow direction to account for the displacement from NNE to SSW of indicator
erratics. In contrast, the single flow event for most later workers was taken to be from the NNE
to the SSW; they invoked aberrations to explain the scratches and furrows that trend NW-SE.

Crescentic marks. In some places, glacial ice created various crescentic marks. Such
marks have been subdivided and named according to the relationship between their curvature
and the direction of flow (Flint, 1971, p. 95; Gilbert, 1906; Harris, 1943; MacClintock, 1953).
Crescentic gouges are convex in the direction of flow. Lunate fractures are concave in the
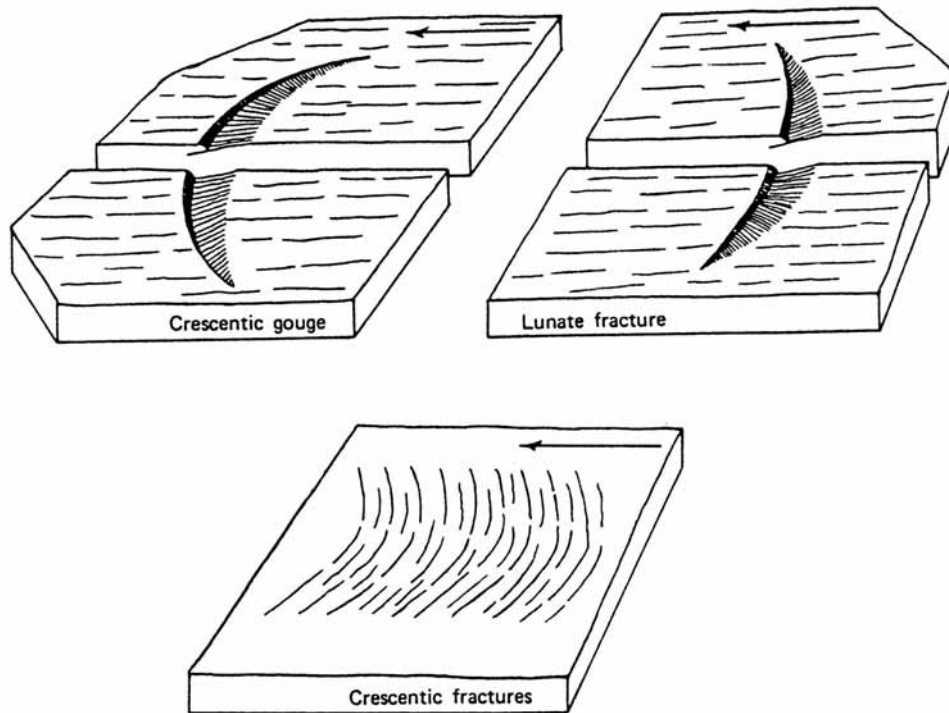direction of flow (Figure 32).

Figure 32 - Three kinds of crescentic marks formed on bedrock by a glacier. Arrows show direction of ice flow. (R. F. Flint, 1971, fig. 5-5, p. 95.)

Crescentic marks can be used to infer the direction of ice flow by means of the asymmetric longitudinal profiles through the centers of the crescents. The ice came from the gently dipping side. The direction of concavity is not reliable.

Roche Moutonnées

The distinctly asymmetric relief features sculpted by a glacier in the bedrock are known as roche moutonnées (Figure 33). These are smooth, broadly rounded and gently dipping on the side from which the ice flowed (a result of the glacier's grinding on an obstruction to flow); but jagged, irregular, and steep on the side toward which the ice flowed [a result of quarrying and plucking along joints where the ice pulled away from the crest of the obstruction].
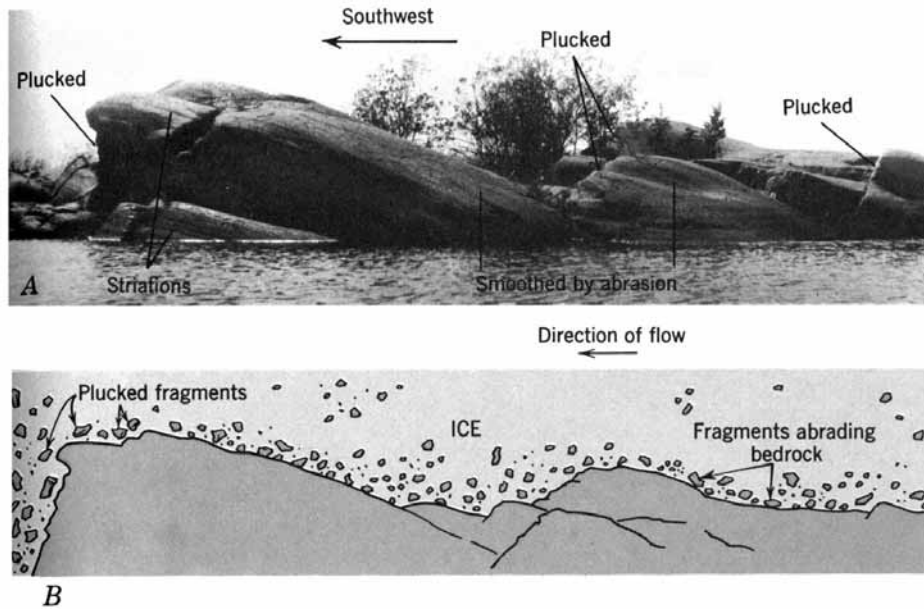
Figure 33 - Roche moutonnées in longitudinal profile. (C. R. Longwell, R. F. Flint, and J. E. Sanders, 1969, fig. 12-7, p. 165.)
A. View of roches moutonn‚es sculpted in Precambrian granitic rock along shores of Lake Athabaska, Saskatchewan, Canada, by glacier that flowed from NE (at R) to SW (at L).
B. Schematic sketch of the Lake Athabaska roche moutonnées beneath a glacier.

The asymmetry described above is based on the effects of a single direction of ice flow. In the New York City region, JES and CM have found many features displaying only part of the morphologic expression of a classic roche moutonnée. The rounded, gently dipping part is present, but the jagged, steep side is not present. Evidently a "classical" roche moutonnée made by one glacier has been modified by flow across and over it of a glacier flowing from a direction that differs by about 45° from the direction of the first glacier.

Drumlins (especially Rock Drumlins)

Another kind of asymmetric feature fashioned by a glacier is an elongate streamlined hill known as a drumlin. The long axis of a drumlin is parallel to the flow direction of the ice; the steeper side is toward the direction from which the ice came (Figure 34). Drumlins consist of till, of bedrock, or of some combination of till and bedrock. The term used by itself implies a feature composed of till. A rock-cored drumlin is one that consists of both till and of bedrock. A rock drumlin consists only of bedrock. (JES does not know why a glacier forms a rock drumlin instead of a roche moutonnée or vice versa.) The point of emphasizing rock drumlins is that their elongation and asymmetry clearly indicate an ice-flow direction. Their shapes can be modified by a later glacier.

Figure 34 - Swarm of drumlins viewed from vertically above in aerial photograph, northern Saskatchewan, Canada, created by a glacier that flowed from NE (upper right) to SW. The small circular lakes give the scale; their diameters are about 1 kilometer. The thin, curviliner light-toned features extending from the center of the view to the upper right margin are parts of an esker complex. (Geological Survey of Canada, Canadian Government Copyright; published in J. E. Sanders, 1981, fig. 13.24, p. 323.)

Data from Indicator Stones

The general name for the study between sedimentary particles and their parent (or "source") deposits in the bedrock is provenance. Because glaciers can transport stones long distances, one commonly finds a collection of glacial particles unlike the bedrock on which the glacial deposits rest. Such stones are known as erratics. If an erratic can be traced to a distinctive source, it becomes an indicator stone.

A few examples of indicator stones found by JES and CM include pyroxenites from the Cortlandt Complex (near Peekskill), the red-brown sandstones/conglomerates from the Newark Supergroup (indicator stones only locally, as in Westchester County and in NW Long Island, where they clearly demonstrate flow from NW to SE, across the Hudson River), the mafic igneous rock (texture ranging from basalt to gabbro) from the Palisades sheet (indicator stones only locally, as in the red-brown sedimentary rocks), the Green Pond Formation (Silurian of northwestern New Jersey and adjacent southeastern New York State), and anthracite (from the Scranton region of northeastern Pennsylvania). The finding by JES of natural erratics of anthracite in the red-brown till along the east side of the Hudson River suggests that the fossiliferous pieces of Carboniferous material found in the Country Club road excavations in the Bronx are glacial erratics and not indicators of a buried Carboniferous basin, as suggested by Zen and Mamay (1968).

Pleistocene Sediments

The Pleistocene sediments consist of several contrasting varieties deposited either directly by now-vanished continental glaciers or as a consequence of the melting of these glaciers. We will be especially interested in the characteristics of till (deposited directly from a glacier) and outwash (deposits made as the glacier melted).

Till

The general name for any sediment deposited directly by the flowing ice of a glacier is till. Typically, till is not stratified and contains a wide range of particle sizes, from boulders to clay.

Outwash

The term outwash refers to any sediment deposited by water melted from a glacier. Outwash includes such contrasting sediments as stream sands and lake clays. The key point about recognizing outwash is the stratification that resulted from the action of water.

Previous Interpretations of Glacial-flow-direction Indicators

As mentioned, the first systematic attempt to record directions of striae and grooves on the bedrock in New York City, was carried out in 1828-29 by L. D. Gale (Mather, 1843). We interpret Gale's results as constituting direct evidence of ice flow from the NW to the SE but

with displacement of erratic indicator stones (anthophyllitic rock and white marble) showing a contrasting direction of NNE to SSW.

Subsequently, other investigators confirmed and extended Gale's results and proposed various interpretations of these indicators of two directions of ice flow. The two ideas analyzed here are: (I) that various changing conditions caused the direction of flow of a single ice sheet to shift with time, and (II) each set of flow directions was made by a single glacier having only one dominant flow direction.

(I) Almost without exception, geologists who have studied the Pleistocene deposits in the New York metropolitan area concur that a single ice sheet of Late Wisconsinan (=Woodfordian) age created all the flow indicators observed. The following review includes what we consider to be critical papers dealing with this topic. We make no claim that this review is comprehensive or complete.

The idea that only one Late Pleistocene ice sheet invaded the New York City region was proposed by T. C. Chamberlin (1895), reinforced by R. D. Salisbury and assistants (1902), and is implicit in all recent papers where the term "lobe" is used with respect to the margin of the ice sheet (for example, Connally and Sirkin, 1970, 1973).

Salisbury and assistants (1902) found that the predominance of ice-flow indicators showed glacial flow from the NNW to the SSE over the Palisades whereas by contrast, such indicators demonstrated that glacial flow over the Watchung ridges had been predominantly from the NNE to the SSW. In his interpretation of these indicators of contrasting directions of ice flow, Salisbury argued that within the margins of an ice sheet are localized zones within which the ice-flow paths are faster than elsewhere. Accordingly, the ice-flow "streamlines" are thought to be crowded close together, as in the sketch map of the region surrounding Lake Michigan (Figure 35). On either side of such supposed zones of concentrated flow, the ice tends to spread out toward each side. In applying this concept to the New York metropolitan area, Salisbury inferred that during the latest glaciation of the New York City region, the axis of fastest-flowing ice had not been down the Hudson Valley, as one might expect on the basis of valley size, but rather followed the Hackensack Valley to the west (Salisbury and assistants, 1902). From this inferred zone of concentrated flow down the Hackensack Valley, they thought that the ice had flowed toward the south-southeast over the Palisades ridge and Manhattan, and toward the south-southwest over the crests of the Watchung Ridges in New Jersey (Figure 36). Salisbury admitted that the regional distribution of erratics of the distinctive Silurian Green Pond Conglomerate from northwestern New Jersey constituted an anomaly to this explanation of marginal-flow divergence within a single glacier as the cause of the divergent orientations of the glacial grooves and -scratches. Salisbury acknowledged that another succession of events which could explain the distribution of erratics of Green Pond Conglomerate involved two glaciations, but he merely mentioned the possibility of two contrasting glaciers.
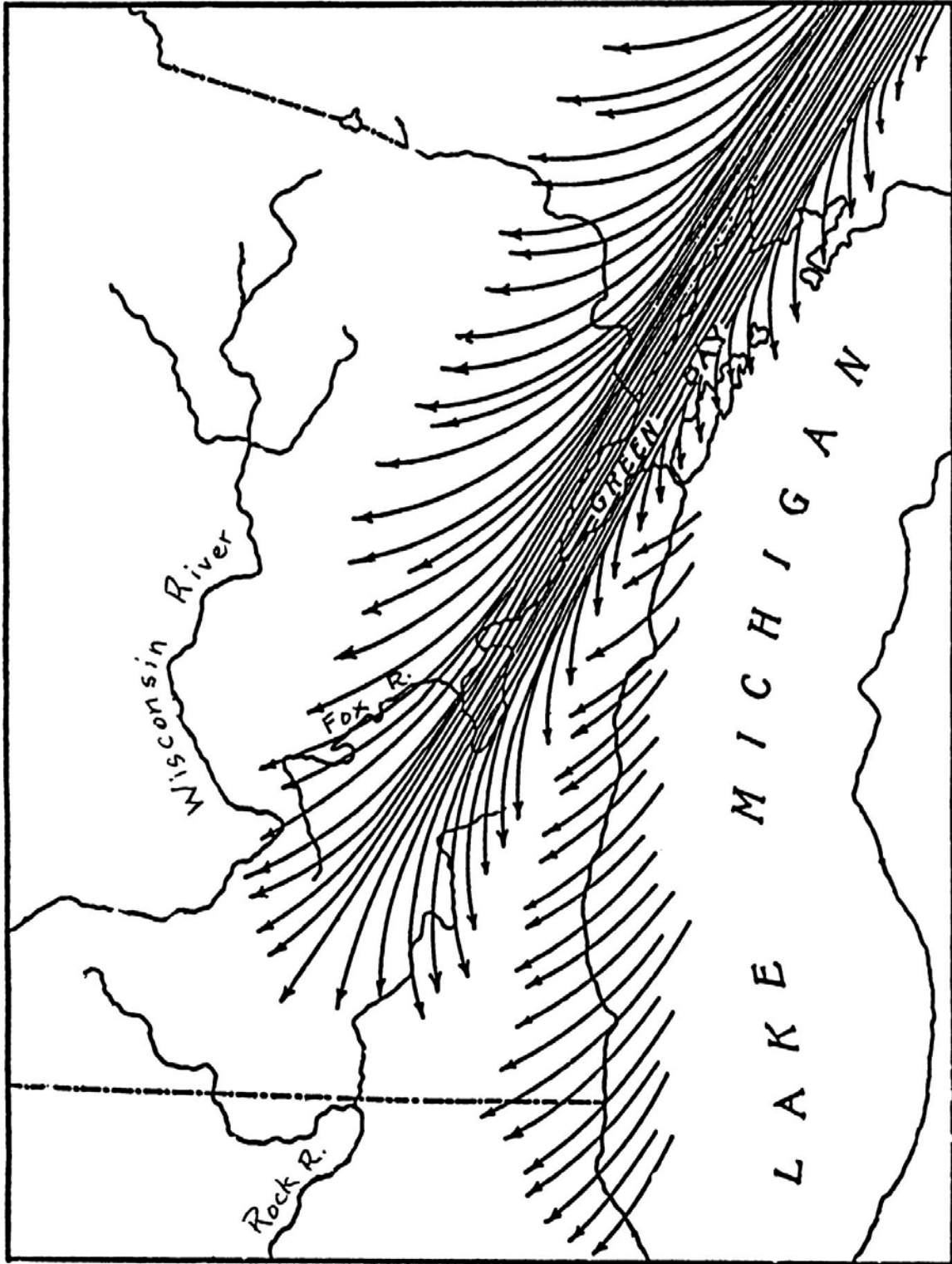
Figure 35 - Sketch map of area west of Lake Michigan (mostly in Wisconsin, but including parts of Michigan and Illinois), showing concept of divergent flow from a narrow zone (centered above Green Bay, Wisconsin) of rapid flow within an ice sheet. (R. D. Salisbury, 1902, fig. 31.)
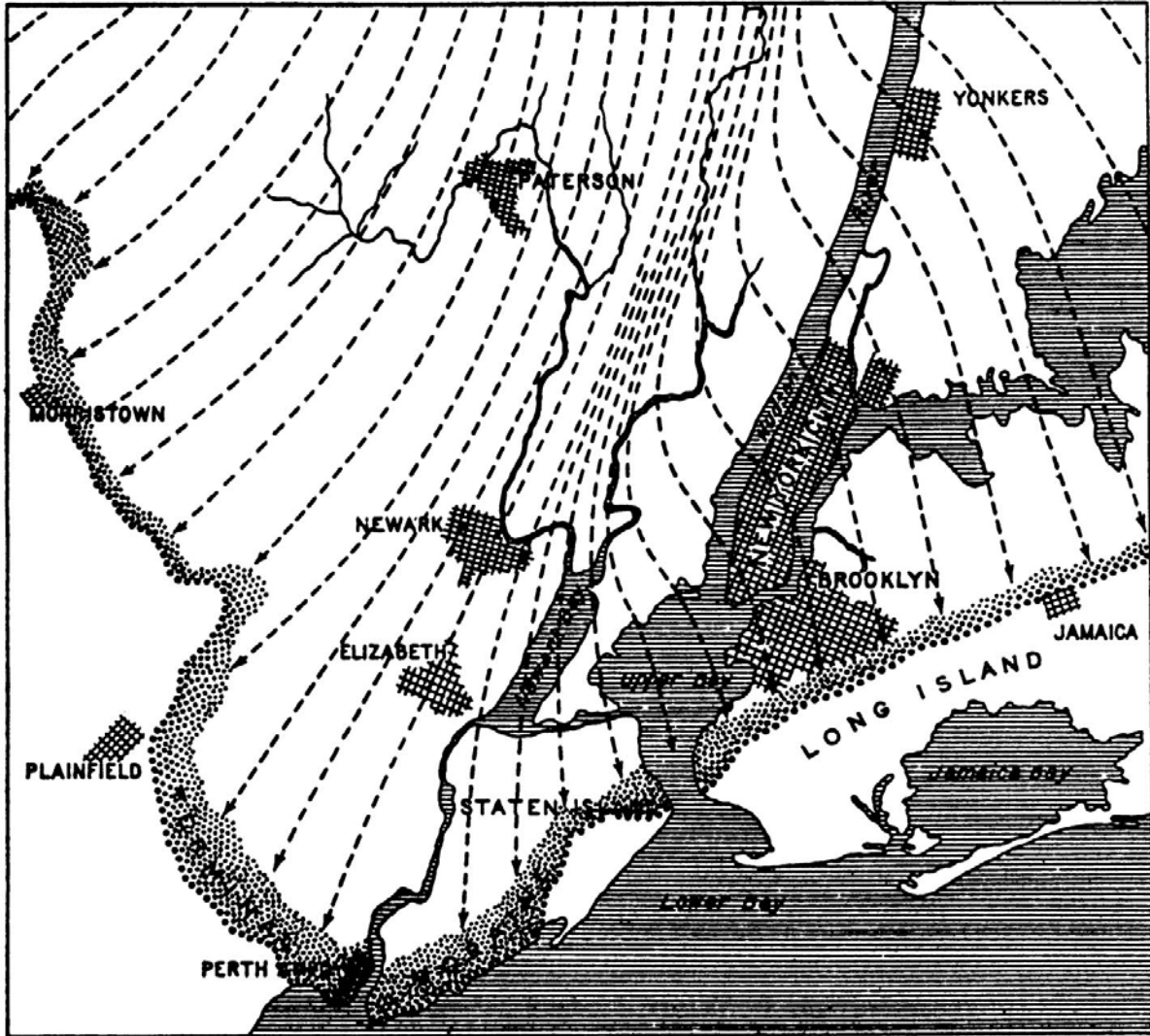
Figure 36 - Map of northeastern New Jersey and southeastern New York showing inferred flow lines in the latest Pleistocene glacier. Further explanation in text. (U. S. Geological Survey, Passaic Folio, No. 157, Figure 11, 1908, rendering of R. D. Salisbury).

Another version of how a single glacier could create flow indicators having several directions is based on the behavior of ice lobes. Such lobes characterize the terminus of a valley glacier that has spread beyond the confining bedrock valley walls. Although the main flow direction of ice in a valley glacier is parallel to the trend of the valley, within the terminal lobe, the spreading ice creates divergent flow paths.

The theoretical background in support of the concept that one and the same continental ice sheet could display multiple flow directions was proposed at the time when the modern version of the Laurentide Ice Sheet was advocated (Flint, 1943). According to Flint, the Laurentide Ice Sheet began as one or more snowfields in the highlands of northeastern Canada. With continued additions of snow, an ice cap appeared and it began to spread southward and

westward. The azimuth from the northeastern Canadian highlands to New York City is 195° or along a line from N15°E to S15°W. After this ice cap had become a full-fledged ice sheet and had attained something close to its full thickness, it is presumed to have itself become a factor in localizing where further snow would fall. Flint inferred that the ice sheet could divert the flow of moisture-bearing winds from the Gulf of Mexico and thus would have acted as an orographic source of precipitation. In other words, the ice sheet forced the air to rise and to be cooled and thus to drop its moisture. Enough snow is therefore thought to have been heaped up at various localities near the outer margin of the ice sheet and thus to have formed ice domes whose relief altered the direction of flow. Thus, the initial direction of regional rectilinear flow toward the SSW as a result of snow supply from northeastern Canada, could change locally to centers of quasi-radial flow under of the influence of the ice domes each of which could display divergent flow patterns, including zones of flow from NNW to SSE. During retreat, the above-described situation would be reversed. The factors responsible for radial ice-dome flow, including sectors from NNW toward the SSE, would cease to operate and those causing rectilinear flow toward the SSW to resume their former pre-eminence. The predicted pattern of flow for each advance of such an ice sheet, therefore, would involve three phases in the following order: (1) rectilinear flow from the NNE toward the SSW; (2) quasi-radial flow from the glacier-marginal ice domes, but locally from the NNW toward the SSE; and (3) rectilinear from the NNE toward the SSW.

Flint opposed the multiple-glacier hypothesis because he was convinced that if two glaciers had flowed over an area and both had extended their influence deep enough to polish and scratch the bedrock, then the younger glacier would obliterate all traces of the older one. Accordingly, he argued that all the striae must have been made by only one glacier, the youngest one.

Figure 37 shows a map of North America with what was for a long time the standard view of how the Pleistocene ice covered Canada and northern United States. Notice that New York is within the flow pattern shown for the Labrador Ice Sheet.

Given the concept that ice from the Labrador center should have been present in New York City, then the expected direction of such glacier flow is from the NNE to the SSW, a direction that is parallel to the Hudson River. However, in Manhattan and on the top of the Palisades Ridge, striae are oriented from about N20°W to S20°E, or even more toward the NW-SE direction. A previous generation of glacial geologists adopted the view of deviated flow from a central lobate glacier. (See Figure 36.)

According to this concept, the main flow of the latest (and, according to many, the only Wisconsinan) glacier was concentrated down the Hackensack lowland, but the ice deviated to its left and crossed the Palisades ridge and New York City on a NW-to-SE course. This concept of a single glacier flowing in a direction that is parallel to the Hudson Valley was reinforced by the results of thousands of engineering borings through the thick bodies of sediment underlying the Hudson, Hackensack, and other valleys that trend NE-SW. These borings show bedrock overlain by a fresh till that is in turn overlain by outwash (sands/gravels and/or lake clays and - silts) that is overlain by estuarine deposits.

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Figure 37 - Reconstruction of North American Pleistocene Ice Sheets with Keewatin center and Labrador center shown as attaining simultaneous maxima. Further explanation in text. (U. S. Geological Survey).

Interpretations of the Pleistocene glacial history of New York City and vicinity have been powerfully influenced by two factors: (1) the two prominent terminal-moraine ridges on Long Island (the older Ronkonkama and younger Harbor Hill moraines); and (2) the subsurface stratigraphic relationships in major valleys that trend NNE-SSW, most notably the Hudson Valley. Both the terminal-moraine ridges and the subsurface stratigraphic units have been ascribed to the latest glaciation, of latest Wisconsinan age, an interval known as the Woodfordian.

The interpretation formulated on the basis of these relationships in New York has left its mark on a far wider area than that of metropolitan greater New York City. Indeed, Long Island's

terminal moraines have been cited as proof that the latest Pleistocene glacier was areally more extensive than its predecessors. The proposition is widely presumed to be valid that the intensity of climatic cooling determined the extent of the ice sheets, that is the colder the climate, the bigger the ice sheets, and vice versa. Given the areal relationships of the Long Island moraines, and applying the widely presumed climate-glacier area proposition, the conclusion followed logically that the climate of latest Wisconsinan time must have been colder than that during earlier glacial episodes.

Study of the hundreds of engineering borings made in connection with bridges and tunnels crossing the Hudson Valley and for highways and other structures in the Hackensack Valley to the west supported the conclusion that the Pleistocene history included only one glacial advance. A fresh-looking till was found to be resting on bedrock and to be overlain by pro-glacial lake sediments, typically varved. These lake sediments in turn are overlain by gray organic silts and/or peats related to the encroachment of the modern sea.

Proponents of multiple glaciers with contrasting flow directions are not numerous and for the most part, their interpretation has been ignored. They have been crushed in the "one-glacier-did-it-all" stampede. One of the earliest advocates of the multiple-glaciers possibility was Woodworth (1901), who found in Long Island City that red-brown till, resting on a striated pavement displaying striae oriented NNW to SSE, composes the Harbor Hill Moraine. Fuller (1914) demonstrated the stratigraphic relationships involved in pre-Wisconsinan glaciations. Our only significant difference from Fuller's work is that he assigned Long Island's two major moraine ridges (older and southern Ronkonkama and younger and northern Harbor Hill) to the Wisconsinan. Based on Woodworth's work in Long Island City and out own results on relative ages of the various glacial features, we assign the Harbor Hill Moraine a pre-Wisconsinan (possibly Illinoian, an age likewise advocated by C. A. Kaye, 1964b) age and the Ronkonkama Moraine to a still-older glaciation.

C. A. Kaye (1982) has interpreted the Pleistocene deposits in the Boston area in terms of multiple glaciations by ice flowing from two contrasting direction: NNW to SSE and NNE to SSW, the same two directions we think are applicable to the New York City region. Kaye based his conclusions on study of striae, crescentic marks, directions of asymmetry of roche moutonnées, long axes of drumlins, and indicator stones. Kaye numbered these tills from I (oldest) to IV (youngest). Tills I, II, and III flowed from the NW to the SE, with means as follows:

Till	Mean flow direction
III	S31°E, +/- 02°
II	S64°E, +/- 18°
I	S23°E, +/- 01°

Using these same features, as mentioned above, we conclude that more than one glacier flowed across the New York region; flow indicators prove that the ice came from not one but rather from several directions. JES has prepared Figures 38 and 39 to show how he interprets the flow patterns of glaciers in the same area of Figure 36. In Figure 38, the ice flowed rectilinearly from NW to SE, across the highest ridges and across the Hudson Valley without deflection. This suggests a thick ice sheet whose flow pattern was governed by the gradient on the top of the glacier. Figure 39 shows the flow from NNE to SSE as resulting from a later glacier. According to JES, the two prominent moraine ridges on Long Island resulted from ice flowing as in Figure 38. The latest glacier, shown in Figure 39, did not reach much of Long Island. It covered parts of Queens and Brooklyn, Manhattan, and Staten Island. What its terminal moraine was like is not yet known.
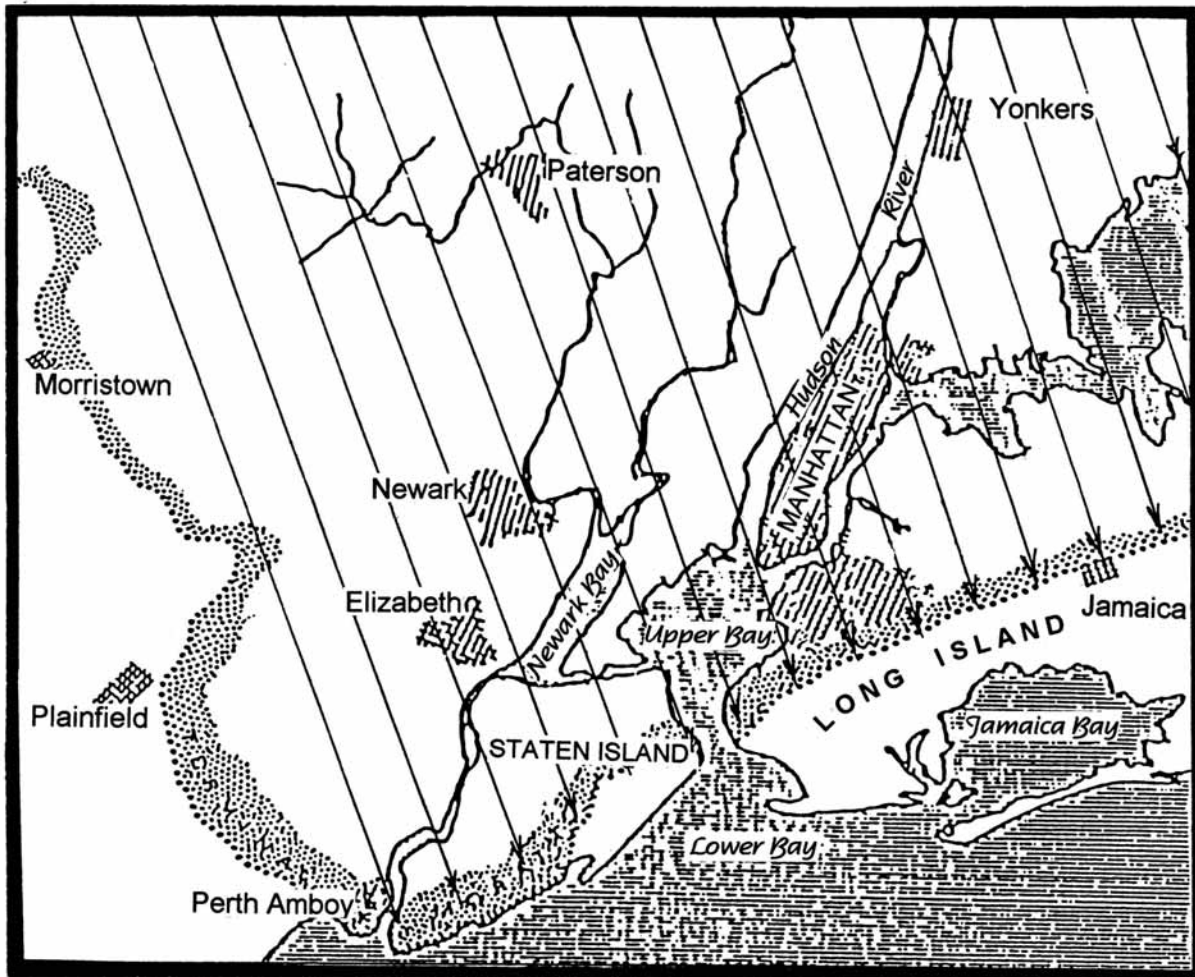

Figure 38 - Rectilinear flow from NW to SE of glacier older than the latest Wisconsinan. This glacier flowed across the Hudson Valley and deposited red-brown till and -outwash on the east side of the Hudson River. (J. E. Sanders).

Figure 39 - Inferred flow pattern of latest Wisconsinan glacier, down the Hudson and Hackensack lowlands from NNE to SSW. This glacier affected only westernmost parts of Long Island; elsewhere, its terminal moraine was along the south coast of Connecticut. (J. E. Sanders).

Evidence for glacial flow from the NW to the SE is not confined to the territory near New York City. Figure 40 shows examples based on swarms of drumlins near Charlevoix, Michigan (northwestern part of southern peninsula) and on indicator stones in New England.
Holocene Sediments Deposited by the Flandrian Submergence

The rapid melting of the Late Wisconsinan ice sheet returned vast quantities of water from the ice back to the oceans. As a result, the sea rose rapidly. This rapid rise of sea level has been named the Flandrian submergence (name derived from northwestern Europe). In the New York City region, the oldest deposit of the rising sea is the so-called gray "organic silt" found in the major river valleys, such as the Hudson. The thickness of the Holocene organic silt ranges up to 150 feet or so, as indicated in borings made for engineering structures.

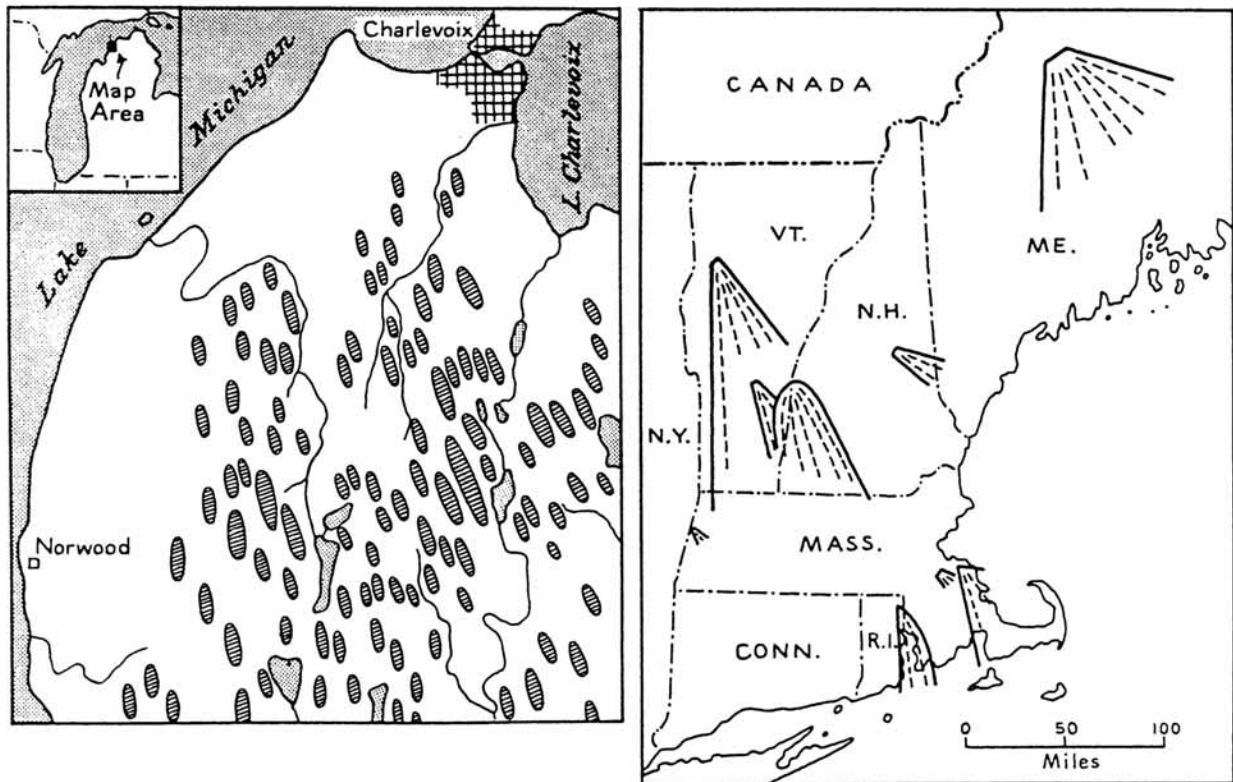**Figure 40** - Sketch maps showing other regions in the United States where glacier flow was from NW to SE.
A. Swarm of drumlins south of Charlevoix, Michigan. (Frank Leverett, and F. B. Taylor, 1915, p. 311; redrawn by L. D. Leet and Sheldon Judson, 1965, fig. 13-20, p. 188.)
B. Boulder trains in New England, all products of regional glacier flow from NW to SE. (J. W. Goldthwait, in R. F. Flint, 1945; redrawn by L. D. Leet and Sheldon Judson, 1965, fig. 13-22, p. 190.)

Once this silt began to be deposited in an area, the pattern has not changed. We note a few points about this Holocene silt. First of all, it is full of gas bubbles. As a result, it is very reflective to sound waves. This means that the silt serves as a blanket which effective precludes the use of ordinary small-boat continuous seismic-reflection profiling, as with sparkers, boomers, and air guns. Many a hopeful investigator has supposed that it would be possible to obtain seismic profiles of the sediments in the Hudson Estuary. An equal number has been defeated; all they ever got was multiples (remember the chorus in the song about Mary Ann McCarthy who went out to dig some clams? "All she ever got was mussels, etc.")

Attempts have been made to date the basal silt from samples obtained at Iona Island and at the Newburgh-Beacon bridge on I-84. Based on samples dated by the radiocarbon method, Newman, Thurber, Zeiss, Rokach, and Musich (1969) concluded that the age of the oldest estuarine silt is 12,000 radiocarbon years. D. Weiss (1974) placed the date at 11,000 years B. P.

(before present). Owens, Stefansson, and Sirkin (1974) compared the clay minerals from the lake sediments with those of the estuarine silt and also performed chemical analyses on the silt. Other papers devoted to the Holocene sediments are by Agron (1980) in the Hackensack meadowlands, New Jersey; and by Averill, Pardi, Newman, and Dineen (1980) for both the Hackensack and Hudson valleys.

New insights into the behavior of the fine sediments in the Hudson Estuary have come from the use of geochemical tracers, from the atmosphere, from discharges of radionuclides from the Indian Point reactors, and from the General Electric capacitor-manufacturing plants at Hudson Falls and Fort Edward (results from the geochemical laboratory at Lamont-Doherty Earth Observatory of Columbia University, by the team headed by H. J. Simpson, and including Richard Bopp, Curt Olsen, and others). Using the vertical distribution in sediment cores of the radioactive isotope of cesium (137; derived from nuclear-weapons tests carried out in the late 1950's and distributed worldwide via the atmosphere), these investigators have found two contrasting depositional settings: (1) marginal flats, where the post-fallout sediment is only a few millimeters thick (equals the modern rate of submergence); and (2) dredged channels, where the thickness of post-fallout sediment ranges up to several tens of centimeters. In the marginal flats, sediment has evidently built up to the profile of equilibrium and new sediment can be added only as this profile is lowered (as it is during submergence). In newly dredged channels, sediment fills in very rapidly, at rates in the tens of centimeters per year (C. R. Olsen, Simpson, Bopp, S. C. Williams, Peng, and Deck, 1978; Simpson, C. R. Olsen, S. C. Williams, and R. M. Trier, 1976).

In the spring of 1974, and again in 1976, two mighty surges of sediments highly contaminated with PCBs from the General Electric plants at Hudson Falls and Fort Edward spread throughout the Hudson Estuary and beyond. Prior to 1973, these sediments were being kept upriver behind the ancient Fort Edward Dam. For reasons of safety, and to prevent a disastrous downriver surge of sediments that would accompany a damburst flood, the Niagara-Mohawk Power Company, owner of the dam, obtained permission from the Federal Power Commission and New York State Department of Environmental Conservation to remove the Fort Edward Dam. Granted this permission, Niagara-Mohawk dismantled the dam, starting in July 1973 and ending in October 1973. Two subsequent floods and a general time of high flows brought about the very result that removal of the dam was supposed to forestall!

The effects of industrial pollution have obliterated the once-fluorishing oysters of the Hudson estuary. In 1966, JES participated in a small experiment of lowering a TV camera and light to the bottom of the Tappan Zee off Irvington. The bottom is paved with dead oyster shells.

In many places, intertidal salt marshes are encroaching on the land as the sea rises. In order to become established, such marshes require a base of tidal sediments, usually silt/mud. But, an established marsh can keep up with a rising sea; and, the marsh spreads out landward as it grows vertically as the water-level rises.

OBJECTIVES

1) To show you some of the stratigraphic- and structural evidence upon which CM has proposed his far-reaching re-interpretation of the "Manhattan Schist."

2) To study features eroded on the bedrock by glaciers and try to convince participants that the dominant direction of glacier flow that can be reconstructed in Central Park is from NW to SE (from across the Hudson Valley) rather than from NNE to SSW (the direction of the most-recent glacier; which was down the Hudson Valley).

3) To become aware of all the improvements Robert Moses made to Central Park in 1934 and especially to follow Moses' first principle, namely that a visit to the Park should be the occasion for having a good time.

LIST OF LOCALITIES TO BE VISITED

STOP 1 - SE of Zoo work shed, Hartland formation and an obscene roche moutonnée.

STOP 2 - E of walkway just N of 65th Street Transverse Road; mylonitic Hartland formation cut by glacial grooves.

STOP 3 - E of walkway near "X" crossing of paths S of "The Dene;" mylonitic Hartland formation and glacial grooves.

STOP 4 - Outcrop W of "The Dene"; two sets of cross-cutting glacial features on polydeformed Hartland formation.

STOP 5 - By "Platform" (outcrop E of "The Dene" and N of playground); beginning of the Cameron's Line thrust zone, glacial features, and outdoorsmen.

STOP 6 - At USGS bench mark S of The Pond; typical Hartland Formation away from the Cameron's Line thrust zone.

STOP 7 - W of the Pond, opposite Avenue of the Americas access to Park; folded and glacially polished Hartland formation.

STOP 8 - On S side of West Drive, near SW boundary of Park; Hartland rocks sheared along F_3 limbs and glacial features.

STOP 9 - On N side of West Drive near bridge over walkway from 7th Avenue; Hartland rocks showing bedding.

STOP 10 - Umpire Rock; Hartland rocks "safe at home".

STOP 11 - E side of walk E of Heckshcer Playground; pegmatite erratic on glacially polished Hartland rocks.

STOP 12 - E of junction of walks N of Stop 11; mildly mylonitic Hartland rocks.

STOP 13 - By the Carousel; the "middle unit" of the Manhattan Formation.

DESCRIPTIONS OF INDIVIDUAL LOCALITIES

The stops listed below provide a planned walk through the geology of some of the better exposures in the south part of Central Park and are identified on the base map provided as Figure 41. This base map is reproduced at the same scale as CM's geologic map of the park. (See Figure 26.) Those interested can reproduce the geologic map onto acetate or mylar to make an overlay to the same scale as the Park map. We will undoubtedly depart from our intended stops to include additional stops as interest and discussion ensue. As such, the stops listed below represent a minimum of our planned stops for the day.

Walking Instructions: Borrowing from the Godfather of Soul, James Brown … Start with the good foot, then .... Leave the Academy on foot and enter the park at the Children's Gate at 64th Street. Turn left toward the Central Park Zoo. Stop 1 is just beyond the promenade.

STOP 1 - SE of Zoo work shed, Hartland formation and an obscene roche moutonnée. [UTM Coordinates: 586.75E / 4513.10N, Central Park quadrangle.]

The exposure consists of gray- and locally brown-weathering muscovite-biotite schist and thin interlayers of biotite granofels, rocks typical of the Hartland Formation (Ɇ-Oh) in New York City. The S_2 foliation consists of parallel thin laminae and local syntectonic granitoid veins, predominates at this exposure and is oriented N80°W, 34°SW. F_3 Z-folds are also obvious with traces of axial surfaces oriented N42°E, 88°SE and F_3 axes plunging 35° into S17°W. Abundant pegmatite veins (some with large books of muscovite) and veinlets create a nubby weathering appearance, but should not be confused with the aluminosilicate-induced nubby weathering of the Ɇ-Om unit of the Manhattan Schist. Some of the pegmatite veins have been folded by the F_3 folds. Local 10-cm thick quartzose segregations are present. An amphibolite, 15 cm thick, can be seen at the south end of the exposure near 63rd Street.

Evidence for SE-directed glacial flow is obvious in the glacially sculpted exposure in the form of large- and small grooves oriented N30°W to N35°W (at the south end of the exposure) and N40°W on top of the exposure. A fake roche moutonnée is the product of drill-and-blast work of Obscene age (the period of geologic time stratigraphically above the Holocene) on the eastern edge of the exposure. Luckily, our glacial hypotheses are not drilled full of holes as the glacial grooves are real.
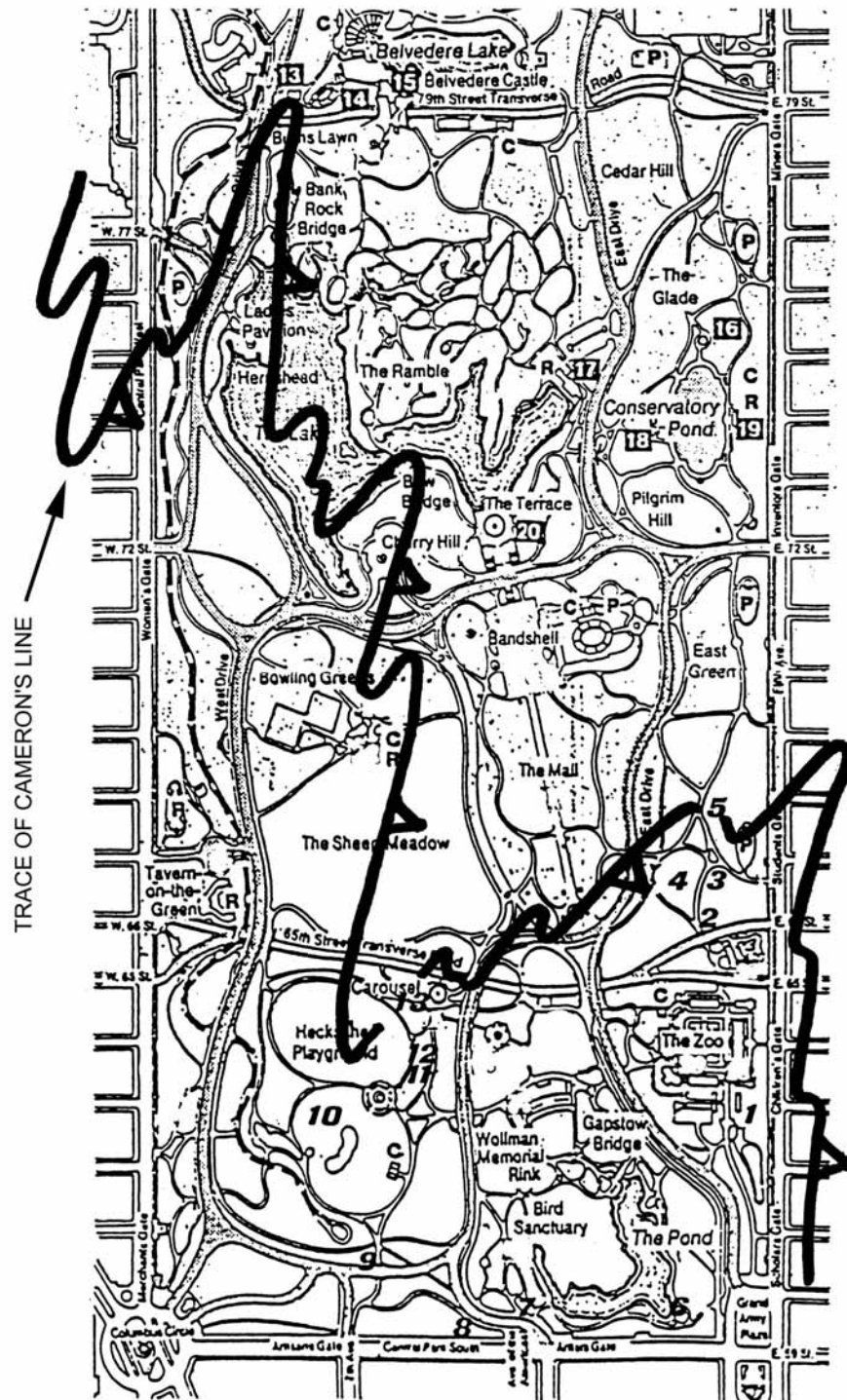
Figure 41 - Location map of Central Park showing our intended Stops 1 through 13. The trace of Cameron's Line (according to CM) is shown for reference. Note that this location map is reproduced at the same scale as Figure 26.

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STOP 2 - E of walkway just N of 65th Street Transverse Road; mylonitic Hartland formation cut by glacial grooves. [UTM Coordinates: 586.85E / 4513.32N, Central Park quadrangle.]

The exposures of Hartland here consist of 4 slabby, gray-weathering vitreous quartzite (thicknesses usually 4 to 5 cm, but locally up to 30 cm), granofels, minor schist and amphibolite with a laminated fabric developed parallel to a composite S_2 foliation. S_2, subparallel S_1 and bedding (S_0), are strongly transposed (oriented N56°E, 45°SE) because of the effects of F_3 Z-folds with axial surfaces trending N50°E, 85°SE. The F_3 folds and associated lineations plunge 24° into S21°W. Away from the limbs of minor F_3 folds, at the NE corner of the first exposure, the S_2 fabric returns to its typical orientation, roughly N53°W, 28°SW. Pegmatites, up to 2 m thick, containing K-feldspar megacrysts up to 30 cm in length, have been intruded parallel to S_3. Vertical healed joints cut the exposures at a high angle (N42°W) and show positive relief producing a reticulate pattern with the dominant lithologic layering and subparallel metamorphic fabrics.

All of the scattered outcrops show the effects of glacial rounding and -polish. Glacial grooves are oriented N47°W to S47°E; they resulted from ice flowing to the SE.

STOP 3 - E of walkway near "X" crossing of paths S of "The Dene;" mylonitic Hartland formation and glacial grooves. [UTM Coordinates: 586.90E / 4513.40N, Central Park quadrangle.]

Similar to the last exposure (still in view toward the S), here the Hartland possesses a pronounced mylonitic fabric suggesting that we are approaching Cameron's Line. The composite $S_2 + S_3$ foliation is oriented N70°E, 49°SE (the effect of transposition by F_3 folding) and has been intruded by numerous foliated lit-par-lit granitoids. In fact, two generations of granitoids cut the bedrock: 1) an older foliated generation, as mentioned above, and 2) a younger sinuous granitoid that cuts across the metamorphic layers.

Glacial grooves are here oriented N25°- to 32°W; they are products of a glacier that flowed SE.

STOP 4 - Outcrop W of "The Dene"; two sets of cross-cutting glacial features on polydeformed Hartland formation. [UTM Coordinates: 586.83E / 4513.40N, Central Park quadrangle.]

This large polished exposure contains rocks similar to the last three stops and shows the effects of superposed F_2 and F_3 folds. The composite $S_2 + S_3$ foliation is oriented N53°E, and is vertical (90°) or dips steeply SE. The bedrock has been cut by two generations of healed fractures, an older one trending N40°W and a younger one, N-S. We will examine the rocks for structural features on the trip day and concentrate here on glacial features.

Obscured by post-glacial weathering on the E end of the exposure a partial pothole greets the observant student of geology. Nearby, glacial grooves are oriented N35°W again, supporting our earlier observations, indicating a SE-directed glacial ice-flow direction. At the NE end of

the exposure a glacial treat awaits our eyes. Here, a subdued roche-moutonnée structure oriented N37°E is cut by N36°W-trending glacial grooves. Thus, one of our older glacial advances has left its indelible mark on the bedrock. (See Table 3.)

STOP 5 - By "Platform" (outcrop E of "The Dene" and N of playground); beginning of the Cameron's Line thrust zone, glacial features, and outdoorsmen. [UTM Coordinates: 586.92E / 4513.43N, Central Park quadrangle.]

At this exposure, we will try to convince you that deep-seated mylonitic faults such as Cameron's Line are not unique single surfaces of dislocation but rather zones of imbricated lithologies (termed mélange) bearing mylonitic fabrics. Here, we see comingled gray-weathering quartzite- and granofels-bearing schist of the Hartland (Є-Oh) and rusty-weathering schist and gneiss of the Manhattan (Є-Om) formations in fault rocks bearing a highly penetrative $S_1 + S_2$ mylonitic foliation. The Є-Om unit is mostly found near the north end of the exposure. Although variable, at the south end of the exposure, the $S_1 + S_2$ mylonitic foliation strikes N68°E and dips 22°SE and can be traced parallel to the axial surfaces of F_2 folds of the S_1 foliation in quartzites. The F_2 folds are reclined (plunge down the dip of their axial surfaces) and plunge 25° into S10°W. Elsewhere, the S_2 mylonitic foliation is oriented N46°W, 27°SW and shows the effects of F_3 folding.

At the north end of the large exposure, where rusty-weathering Є-Om predominates, Є-Oh granofels layers, 30 to 50 cm thick, can be seen "floating" in a schistose matrix. Such intermixing is perhaps the product of shearing and imbrication related to the formation of mélange within the Cameron's Line thrust zone. Here the S_2 foliation swings to N75°W, 35°SW.

The folds- and fabrics related to the F_2- and older folds are strongly reoriented by F_3 folds. Tight- to isoclinal F_3 folds plunge 25° into S15°W with axial surfaces oriented N28°E, 68°SE. Beautiful examples of F_2 x F_3 interference patterns are found in this exposure - be on the lookout.

Glacial plucking has here been facilitated by joints oriented N85°E, 70°NW. A broad roche-moutonnée structure oriented N10°E occurs at the north end of the exposure and glacial grooves and troughs are found elsewhere oriented N32°W but crosscutting relationships were not observed on our field trip runthrough on September 9, 1993. Based on what we saw at Stop 4, we suspect that the NW-trending grooves are younger than the roche-moutonnée structure.

Time permitting, we may walk northward at this point to examine nearby exposures for lithologic- and glacial features. Retrace the walk back toward the zoo (rest stop) and then continue to the SE corner of the park for Stop 6.

STOP 6 - At USGS bench mark S of The Pond; typical Hartland Formation away from the Cameron's Line thrust zone. [UTM Coordinates: 586.58E / 4512.93N, Central Park quadrangle.]

Rocks of the Hartland Formation here consist of their typical gray-weathering, highly muscovitic schist and massive, structureless granofels in an exposure at the SE corner of "The Pond", across from the Plaza Hotel. The granofels layers are quite numerous; their thickness varies from 3 cm to 50 cm and they are separated by schistose layers, 3 cm to 4 cm thick, that are exceedingly rich in muscovite (only about 5% biotite). Bedding is thus preserved and our interpretation is that the protoliths of the granofels layers were turbidites. With a little imagination, relict grading indicates that bedding tops twoard the NW with S_0 and parallel S_2 and S_3 oriented N48°E, 70° to 80°NW.

Upright F_3 synformal folds of S_0 and S_2 plunge 20° into S45°W with axial surfaces oriented N45°E, 85°SE. A marked difference in mechanical behavior is indicated as the granofels layers show only large-scale warping at the hands of F_3 folds yet the schistose interlayers are strongly folded and crenulated. In addition, four sets of slip- and rock cleavages cut the older fabrics (N32°W, 78°SW; N24°E, 76°NW; N15°W, 65°SW; N10°E, 73 SE). Muscovite-rich pegmatites locally have been intruded parallel to the S_3 foliation. Near their contacts with the metamorphic strata one can find a veritable "library" of muscovite "books."

Glacial grooves are oriented N32°W indicating SE-directed glacial-ice flow.

STOP 7 - W of the Pond, opposite Avenue of the Americas access to Park; folded and glacially polished Hartland formation. [UTM Coordinates: 586.39E / 4513.05N, Central Park quadrangle.]

Muscovite schist and interlayered granofels of the Hartland are cut by open warps of the composite $S_2 + S_3$ foliation. These folds, which must postdate the F_3 folds, plunge southward at 51° with NE-trending axial surfaces (precise measurements are tough here). A minor shear zone in the center of the exposure cuts through a 10-cm-thick layer of amphibolite and an F_2 reclined fold refolded by F_3 occurs on the south end of the exposure.

Glacial grooves are here oriented N28°W and a subdued roche moutonnée structure is oriented N40°E. On our pre-trip visit, we were not able to establish any cross-cutting relationships. We observed SSW-oriented chattermarks (Glacier IV?) on the northward-sloping surface of the roche moutonnée.

STOP 8 - On S side of West Drive, near SW boundary of Park; Hartland rocks sheared along F_3 limbs and glacial features. [UTM Coordinates: 586.32E / 4513.04N, Central Park quadrangle.]

The effects of shearing along the limbs of F_3 folds here produce a penetrative foliation oriented N32°E, 90° in highly muscovitic rocks of the Hartland Formation. The effects of rounding and smoothing of the bedrock surface here are quite obvious as are glacial grooves oriented N38°W.

STOP 9 - On N side of West Drive near bridge over walkway from 7th Avenue; Hartland rocks showing bedding. [UTM Coordinates: 586.27E / 4513.20N, Central Park quadrangle.]

Pronounced interbedding of granofels and muscovite schist here typify the Hartland formation. Bedding (S_0) and the S_2 foliation are oriented N43°W, 30°SW near the vicinity of an F_3 antiformal hinge area (CM's 7th Avenue Antiform). The F_2 folds here show Z-fold symmetry indicating we are on the eastern side of the south-plunging antiform.

STOP 10 - Umpire Rock; Hartland rocks "safe at home". [UTM Coordinates: 586.27E / 4513.37N, Central Park quadrangle.]

Umpire Rock is the most-spectacular natural exposure in the southern part of Central Park. Here, rocks of the Hartland Formation show the superposed effects of F_2 and F_3 folds, abundant syn- and post-tectonic pegmatite intrusives, brittle faults, and numerous glacial features. The rocks consist of interlayered muscovite schist and granofels that have been cut by numerous granitoids. F_2 fold hinges are locally preserved but the glacial smoothing of the outcrop surface inhibits direct measurement of plunge orientation. The S_2 axial-planar foliation is strongly folded here but possesses an average orientation (enveloping surface) of N77°W, 21°SW.

F_3 Z-folds vary from open- to tight- to isoclinal in profile and plunge 22° into S25°W with axial surfaces oriented N35°E, 72°SE. Beautiful interference patterns result from the superposition of F_2 and F_3 folds. Late-stage open warps with southward plunges are locally developed (similar to Stop 7 but with kinder, gentler plunges as first described by former President George Bush). Some pegmatites are syntectonic (foliated) and were intruded parallel to S_2. Other granitoids are thin aplites oriented N50°E and crosscut all structural fabrics. Even-younger pegmatites cut the aplites. At least two brittle faults oriented N32°E cut the exposure; the one on the eastern edge of the outcrop shows a crumbly gouge zone roughly 3 m thick.

Perhaps the most-obvious geologic features here are of glacial origin. At the NW edge of the exposure, glacial meltwaters have modified spectacular glacial troughs oriented N28°W. These troughs are related to the overall SE-directed roche-moutonnée shape of the exposure with its steep dropoff toward the playground area. A potpourri of glacial erratics can be found on this outcrop. On our brief pre-trip visit, we identified erratics of Palisades diabase and hornfelsic Lockatong Formation from the Newark basin W of the Hudson River, Hartland Formation, granite, and diorite. Evidence of our youngest glacier (the one from the NNE) is here in the form of a Hartland glacial erratic that has been tipped upside down immediately south of its former jointed home. The fact that this erratic has not been displaced or removed by SE-directed ice strongly suggests that our youngest glacier (the "Woodfordian") was responsible for its short journey.

Around the steep, north-facing wall of the exposure, note the glacial grooves oriented N46°W and the grooves oriented N35°W on the eroded outcrops immediately north of the north-facing wall. Of additional structural interest, the north-facing wall offers a rare glimpse at the

shallow dip of the S_2 foliation and a sub-parallel granitoid sill, all folded by F_3? or younger open warps.

STOP 11 - E side of walk E of Heckshcer Playground; pegmatite erratic on glacially polished Hartland rocks. [UTM Coordinates: 586.39E / 4513.38N, Central Park quadrangle.]

The most-obvious feature of this stop is the 2m-high K-feldspar megacrystic pegmatite erratic. The erratic rests on rocks of the Hartland that have been scored by N38°W glacial grooves. F_3 S-folds are locally found in the exposure.

STOP 12 - E of junction of walks N of Stop 11; mildly mylonitic Hartland rocks. [UTM Coordinates: 586.39E / 4513.39N, Central Park quadrangle.]

The Hartland Formation here shows some evidence for lithologic mixing; rocks of the "middle unit of the Manhattan formation," are present in the form of inclusions consisting of wisps- and shreds of aluminosilicate-bearing, rusty- to maroon-weathering schist. The outlines of the wisps and shreds are probably masked by shearing along S_2 and S_3 (a convenient circumstance that requires little leg-to-leg hopping by CM). S_2 is well developed here and is oriented N68°W, 42°SW. F_3 folds are not hard to spot with their typical southward plunges and steep NE-trending axial surfaces.

STOP 13 - By the Carousel; the "middle unit" of the Manhattan Formation. [UTM Coordinates: 586.45E / 4513.43N, Central Park quadrangle.]

The exposure of rocks immediately west of The Carousel show the rusty- to maroon-weathering typical of CM's "middle unit of the Manhattan Formation" (Unit C̶-Om). Layers- and lenses of kyanite+sillimanite+magnetite weather in positive relief and outline the S_2 foliation which is largely mylonitic. Here, S_2 is variable but oriented N70°E, 25°SE because of pervasive F_3 folds plunging 34° into S25°W. The F_3 axial surfaces trend N42°E, 68°SE. CM maps this area as the beginning of the Cameron's Line thrust zone and links these exposures to those found at our earlier Stop 5.

From here, after a brief interlude on The Carousel, we will begin a freeform mapping exercise to regions of the park north of Stop 13, hoping to further support our visions of the structural- and glacial history of the park. We plan to end somewhere near the American Museum of Natural History and then walk back to the Academy.

TABLES

Table 01 - GEOLOGIC TIME CHART
(with selected major geologic events from southeastern New York and vicinity)

ERA Periods (Epochs)	Years (Ma)	Selected Major Events
CENOZOIC		
(Holocene)	0.1	Rising sea forms Hudson Estuary, Long Island Sound, and other bays. Barrier islands form and migrate.
(Pleistocene)	1.6	Melting of last glaciers forms large lakes. Drainage from Great Lakes overflows into Hudson Valley. Dam at The Narrows suddenly breached and flood waters erode Hudson shelf valley. Repeated continental glaciation with five? glaciers flowing from NW and NE form moraine ridges on Long Island.
(Pliocene)	6.2	Regional uplift, tilting and erosion of coastal-plain strata; sea level drops. Depression eroded that later becomes Long Island Sound.
(Miocene)	26.2	Fans spread E and SE from Appalachians and push back sea. Last widespread marine unit in coastal-plain strata.
MESOZOIC	66.5	
(Cretaceous)		
	96	Passive eastern margin of North American plate subsides and sediments (the coastal-plain strata) accumulate.
	131	(Passive-margin sequence II).
(Jurassic)		Baltimore Canyon Trough forms and fills with 8,000 feet of pre-Cretaceous sediments.
(Triassic)	190	Atlantic Ocean starts to open. Newark basins deformed, arched, eroded. Continued filling of subsiding Newark basins and mafic igneous activity both extrusive and intrusive. Newark basins form and fill with non-marine sediments.
PALEOZOIC	245	
(Permian)		Pre-Newark erosion surface formed.
	260	**Appalachian orogeny.** (Terminal stage.) Folding, overthrusting,

96

and metamorphism of Rhode Island coal basins; granites intruded.

(Carboniferous)		Faulting, folding, and metamorphism in New York City area. Southeastern New York undergoes continued uplift and erosion.
(Devonian)	365	**Acadian orogeny.** Deep burial of sedimentary strata. Faulting, folding, and metamorphism in New York City area. Peekskill Granite and Acadian granites intruded.
(Silurian)		
	440	**Taconic orogeny.** Intense deformation and metamorphism.
	450	Cortlandt Complex and related rocks intrude Taconian suture zone. (Cameron's Line). Arc-continent collision.
(Ordovician)		Great overthrusting from ocean toward continent. Taconic deep-water strata thrust above shallow-water strata. Ultramafic rocks (oceanic lithosphere) sliced off and transported above deposits of continental shelf.
(Cambrian)		Shallow-water clastics and carbonates accumulate in west of basin (= Sauk Sequence; protoliths of the Lowerre Quartzite, Inwood Marble, part of Manhattan Schist Fm.). Deep-water terrigenous silts form to east. (= Taconic Sequence; protoliths of Hartland Formation, parts of Manhattan Schist Fm.). (Passive-margin sequence I).

PROTEROZOIC

	570	Period of uplift and erosion followed by subsidence of margin.
(Z)	600	Rifting with rift sediments, volcanism, and intrusive activity. (Ned Mountain, Pound Ridge, and Yonkers gneiss protoliths).
(Y)	1100	**Grenville orogeny.** Sediments and volcanics deposited, compressive deformation, intrusive activity, and granulite facies metamorphism. (Fordham Gneiss, Hudson Highlands and related rocks).

ARCHEOZOIC

	2600	No record in New York.
	4600	Solar system (including Earth) forms.

Table 02
Generalized Descriptions of Major Geologic "Layers", SE New York State and Vicinity

This geologic table is a tangible result of the On-The-Rocks Field Trip Program conducted by Drs. John E. Sanders and Charles Merguerian between 1988 and 1998. In Stenoan and Huttonian delight, we here present the seven layer cake model that has proved so effective in simplifying the complex geology of the

region. Under continual scrutiny and improvement, we provide this updated web-based information as a public service to all students and educators of geology. We encourage any comments, additions, or corrections. References cited can be sought by following this link.

LAYER VII - QUATERNARY SEDIMENTS

A blanket of irregular thickness [up to 50 m or more] overlying and more or less covering all older bedrock units. Includes four or five tills of several ages each of which was deposited by a continental glacier that flowed across the region from one of two contrasting directions: (1) from N10°E to S10°W (direction from Labrador center and down the Hudson Valley), or (2) from N20°W to S20°E (direction from Keewatin center in Hudson's Bay region of Canada and across the Hudson Valley). The inferred relationship of the five tills is as follows from youngest [I] to oldest [V]. [I] - Yellow-brown to gray till from NNE to SSW, [II] - red-brown till from NW to SE, [III] - red-brown till from NW to SE, and [IV] - yellow-brown to gray till from NNE to SSW, and [V] - red-brown till from NW to SE containing decayed stones (Sanders and Merguerian, 1991a,b, 1992, 1994a, b; Sanders, Merguerian, and Mills, 1993; Sanders and others, 1997; Merguerian and Sanders, 1996). Quaternary sediments consist chiefly of till and outwash. On Long Island, outwash (sand and gravel) and glacial lake sediment predominates and till is minor and local. By contrast, on Staten Island, tills and interstratified lake sediments predominate and sandy outwash appears only locally, near Great Kills beach.

[Pliocene episode of extensive and rapid epeirogenic uplift of New England and deep erosion of major river valleys, including the excavation of the prominent inner lowland alongside the coastal-plain cuesta; a part of the modern landscape in New Jersey, but submerged in part to form Long Island Sound].

~~~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~~~

LAYER VI - COASTAL-PLAIN STRATA (L. Cretaceous to U. Miocene; products of Passive Continental Margin II - Atlantic).

Marine- and nonmarine sands and clays, present beneath the Quaternary sediments on Long Island (but exposed locally in NW Long Island and on SW Staten Island) and forming a wide outcrop belt in NE New Jersey. These strata underlie the submerged continental terrace. The basal unit (L. Cretaceous from Maryland southward, but U. Cretaceous in vicinity of New York City) overlaps deformed- and eroded Newark strata and older formations. Also includes thick (2000 m) L. Cretaceous sands and shales filling the offshore Baltimore Canyon Trough. At the top are Miocene marine- and coastal units that are coarser than lower strata and in many localities SW of New Jersey, overstep farther inland than older coastal-plain strata. Capping unit is a thin (<50 m) sheet of yellow gravel (U. Miocene or L. Pliocene?) that was prograded as SE-directed fans from the Appalachians pushed back the sea. Eroded Newark debris is present in L. Cretaceous sands, but in U. Cretaceous through Miocene units, Newark-age redbed debris is conspicuously absent. This relationship is considered to be proof that the coastal-plain

formations previously buried the Newark basins so that no Newark-age debris was available until after the Pliocene period of great regional uplift and erosion. The presence of resistant heavy minerals derived from the Proterozoic highlands part of the Appalachians within all coastal-plain sands indicates that the coastal-plain strata did not cover the central highlands of the Appalachians.

[Mid-Jurassic to Late Jurassic episode of regional arching of Newark basin-filling strata and end of sediment accumulation in Newark basin; multiple episodes of deformation including oroclinal "bending" of entire Appalachian chain in NE Pennsylvania (Carey, 1955), and one or more episodes of intrusion of mafic igneous rocks, of folding, of normal faulting, and of strike-slip faulting (Merguerian and Sanders, 1994b). Great uplift and erosion, ending with formation of Fall-Zone planation surface].

~~~~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~~~~

LAYER V - NEWARK BASIN-FILLING STRATA (Upper Triassic and Lower Jurassic)

Newark-age strata unconformably overlie folded- and metamorphosed Paleozoic strata of Layer II and some of the Proterozoic formations of Layer I; are in fault contact with other Proterozoic formations of the Highlands complex. Cobbles and boulders in basin-marginal rudites near Ramapo Fault include mostly rocks from Layers III, IIB, and IIA(W), which formerly blanketed the Proterozoic now at the surface on the much-elevated Ramapo Mountains block. The thick (possibly 8 or 9 km) strata filling the Newark basin are nonmarine.

In addition to the basin-marginal rudites, the sediments include fluvial- and varied deposits of large lakes whose levels shifted cyclically in response to climate cycles evidently related to astronomic forcing. A notable lake deposit includes the Lockatong Formation, with its analcime-rich black argillites, which attains a maximum thickness of about 450 m in the Delaware River valley area. Interbedded with the Jurassic part of the Newark strata are three extrusive complexes, each 100 to 300 m thick, whose resistant tilted edges now underlie the curvilinear ridges of the Watchung Mountains in north-central New Jersey. Boulders of vesicular basalt in basin-marginal rudites prove that locally, the lava flows extended northwestward across one or more of the basin-marginal faults and onto a block that was later elevated and eroded. The thick (ca. 300 m) Palisades intrusive sheet is concordant in its central parts, where it intrudes the Lockatong at a level about 400 m above the base of the Newark strata. To the NE and SW, however, the sheet is discordant and cuts higher strata (Merguerian and Sanders, 1995a). Contact relationships and the discovery of clastic dikes at the base of the Palisades in Fort Lee, New Jersey, suggest that the mafic magma responsible for the Palisades was originally intruded at relatively shallow depths (roughly 3 to 4 km) according to Merguerian and Sanders (1995b).

Xenoliths and screens of both Stockton Arkose and Lockatong Argillite are present near the base of the sill. Locally, marginal zones of some xenoliths were melted to form granitic rocks (examples: the trondhjemite formed from the Lockatong Argillite at the Graniteville

quarry, Staten Island, described by Benimoff and Sclar, 1984; and a "re-composed" augite granite associated with pieces of Stockton Arkose at Weehawken and Jersey City, described by J. V. Lewis, 1908, p. 135-137).

[**Appalachian terminal orogeny**; large-scale overthrusts of strata over strata (as in the bedding thrusts of the "Little Mountains east of the Catskills" and in the strata underlying the NW side of the Appalachian Great Valley), of basement over strata (in the outliers NW of the Hudson Highlands, and possibly also in many parts of the Highlands themselves), and presumably also of basement over basement (localities not yet identified). High-grade metamorphism of Coal Measures and intrusion of granites in Rhode Island dated at 270 Ma. Extensive uplift and erosion, ending with the formation of the pre-Newark peneplain].

~~~~~~~~~~~~~~~~~~~~~~**Surface of unconformity**~~~~~~~~~~~~~~~~~~~~~~

LAYER IV - COAL MEASURES AND RELATED STRATA (Carboniferous)

Mostly nonmarine coarse strata, about 6 km thick, including thick coals altered to anthracite grade, now preserved only in tight synclines in the Anthracite district, near Scranton, NE Pennsylvania; inferred to have formerly extended NE far enough to have buried the Catskills and vicinity in eastern New York State (Friedman and Sanders, 1982, 1983).

[**Acadian orogeny**; great thermal activity and folding, including metamorphism on a regional scale, ductile deformation, and intrusion of granites; dated at ~360 Ma].

LAYER III - MOSTLY MARINE STRATA OF APPALACHIAN BASIN AND CATSKILLS (Carbonates and terrigenous strata of Devonian and Silurian age)

(Western Facies)	(Eastern Facies)
Catskill Plateau, Delaware Valley monocline, and "Little Mountains" NW of Hudson-Great Valley lowland.	SE of Hudson-Great Valley lowland in Schunnemunk-Bellvale graben.
Kaaterskill redbeds and cgls.	Schunnemunk Cgl.
Ashokan Flags (large cross strata)	Bellvale Fm., upper unit
Mount Marion Fm. (graded layers, marine)	Bellvale Fm., lower unit (graded layers, marine)
Bakoven Black Shale	Cornwall Black Shale
Onondaga Limestone	
Schoharie buff siltstone	Pine Hill Formation
Esopus Formation	Esopus Formation
Glenerie Chert	

Connelly Conglomerate	Connelly Conglomerate
Central Valley Sandstone	
Carbonates of Helderberg Group	Carbonates of Helderberg Group
Manlius Limestone	
Rondout Formation	Rondout Formation
Decker Formation	
Binnewater Sandstone	Poxono Island Formation
High Falls Shale	Longwood Red Shale
Shawangunk Formation	Green Pond Conglomerate

[**Taconic orogeny**; 480 Ma deep-seated folding, dynamothermal metamorphism and mafic- to ultramafic (alkalic) igneous intrusive activity (dated in the range of 470 to 430 Ma) across suture zone (Cameron's Line-St. Nicholas thrust zones). Underthrusting of shallow-water western carbonates of Sauk Sequence below supracrustal deep-water eastern Taconic strata and imbrication of former Sauk-Tippecanoe margin. Long-distance transport of strata over strata has been demonstrated; less certain locally is proof of basement thrust over strata and of basement shifted over basement. In Newfoundland, a full ophiolite sequence, 10 km thick, has been thrust over shelf-type sedimentary strata].

~~~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~~~

LAYER II - CAMBRO-ORDOVICIAN CONTINENTAL-MARGIN COVER (Products of Passive Continental Margin I - Iapetus). Subdivided into two sub layers, IIB and IIA. Layer IIA is further subdivided into western- and eastern facies.

LAYER IIB - TIPPECANOE SEQUENCE - Middle Ordovician flysch with basal limestone (Balmville, Jacksonburg limestones).

Not metamorphosed / Metamorphosed
Martinsburg Fm. / Manhattan Schist (Om - lower unit).
Normanskill Fm. / Annsville Phyllite

Subaerial exposure; karst features form on Sauk (Layer IIA[W]) platform.

~~~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~~~
LAYER IIA[W] - SAUK SEQUENCE   LAYER IIA[E] - TACONIC SEQUENCE

Western shallow-water platform (L. Cambrian- M. Ordovician)	Eastern deep-water zone (L. Cambrian-M. Ordovician)

Copake Limestone	Stockbridge
Rochdale Limestone	or Inwood Marbles
Halcyon Lake Fm.	
Briarcliff Dolostone	(C-Oh) Hartland Fm.
Pine Plains Fm.	(C-Om) Manhattan Fm.
Stissing Dolostone	(in part).
Poughquag Quartzite	
Lowerre Quartzite [Base not known]	

[**Pre-Iapetus Rifting Event**; extensional tectonics, volcanism, rift-facies sedimentation, and plutonic igneous activity precedes development of Iapetus [Layer II = passive continental margin I] ocean basin. Extensional interval yields protoliths of Pound Ridge Gneiss, Yonkers granitoid gneisses, and the Ned Mountain Formation (Brock, 1989, 1993). Followed by a period of uplift and erosion. In New Jersey, metamorphosed rift facies rocks are mapped as the Chestnut Hill Formation of A. A. Drake, Jr. (1984)].

~~~~~~~~~~~~~~~~~~~~~**Surface of unconformity**~~~~~~~~~~~~~~~~~~~~~

LAYER I - PROTEROZOIC BASEMENT ROCKS

Many individual lithologic units including Proterozoic Z and Y ortho- and paragneiss, granitoid rocks, metavolcanic- and metasedimentary rocks identified, but only a few attempts have been made to decipher the stratigraphic relationships; hence, the three-dimensional structural relationships remain obscure.

~~~~~~~~~~~~~~~~~~~~~**Surface of unconformity**~~~~~~~~~~~~~~~~~~~~~

[**Grenville orogeny**; deformation, metamorphism, and plutonism dated about 1,100 Ma. After the orogeny, an extensive period of uplift and erosion begins. Grenville-aged (Proterozoic Y) basement rocks include the Fordham Gneiss of Westchester County, the Bronx, and the subsurface of western Long Island (Queens and Brooklyn Sections, NYC Water Tunnel #3), the Hudson Highland-Reading Prong terrane, the Franklin Marble Belt and associated rocks, and the New Milford, Housatonic, Berkshire, and Green Mountain Massifs.]

~~~~~~~~~~~~~~~~~~~~~**Surface of unconformity**~~~~~~~~~~~~~~~~~~~~~

In New Jersey and Pennsylvania rocks older than the Franklin Marble Belt and associated rocks include the Losee Metamorphic Suite. Unconformably beneath the Losee, in Pennsylvania, Proterozoic X rocks of the Hexenkopf Complex crop out.

Table 03 – Proposed new classification of the Pleistocene deposits of New York City and vicinity
(Sanders and Merguerian, 1998, Table 2)

Age	Till No.	Ice-flow Direction	Description; remarks
Late Wisconsinan ("Woodfordian"?)	I	NNE to SSW	Gray-brown till in Westchester Co., Staten Is., Brooklyn, & Queens (but not present on rest of Long Island); Hamden Till in CT with terminal moraine lying along the S coast of CT; gray lake sediments at Croton Point Park, Westchester Co.
Mid-Wisconsinan (?)			Paleosol on Till II, SW Staten Island.
Early Wisconsinan(?)	II	NW to SE	Harbor Hill Terminal Moraine and associated outwash (Bellmore Fm. in Jones Beach subsurface); Lake Chamberlain Till in southern CT.
Sangamonian(?)			Wantagh Fm. (in Jones Beach subsurface).
	IIIA	NW to SE	Ronkonkoma Terminal Moraine and associated outwash (Merrick Fm. in Jones Beach subsurface).
Illinoian(?)	IIIB		Manhasset Fm. of Fuller (with middle Montauk Till Member; in lower member, coarse delta foresets (including debris flows) deposited in Proglacial Lake Long Island dammed in on S by pre-Ronkonkoma terminal moraine.
	IIIC		
Yarmouthian			Jacob Sand, Gardiners Clay.
Kansan(?)	IV	NNE to SSW	Gray till with decayed stones at Teller's Point (Croton Point Park, Westchester Co.); gray till with green metavolcanic stones, Target Rock, LI.
Aftonian(?)			No deposits; deep chemical decay of Till V.
Nebraskan (?)	V	NW to SE	Reddish-brown decayed-stone till and -outwash at AKR Co., Staten Island, and at Garvies Point, Long Island; Jameco Gravel fills subsurface valley in SW Queens.

Pre-glacial (?) Mannetto Gravel fills subsurface valleys.

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