BRITTLE FAULTS (RAMAPO FAULT) AND PHYLLONITIC DUCTILE SHEAR ZONES IN THE BASEMENT ROCKS OF THE RAMAPO SEISMIC ZONES NEW YORK AND NEW JERSEY, AND THEIR RELATIONSHIP TO CURRENT SEISMICITY

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Introduction and rationale for investigations

Field investigations at the northern end of the Newark basin begun more than 10 years ago led to the publication of several articles (Ratcliffe, 1971; Ratcliffe and others, 1972) in which a case was made for long continued fault activity in the vicinity of the border fault (Ramapo fault) in New York and New Jersey. These articles also called attention to the observation that a series of low-level earthquakes appears to be spatially associated with these ancient faults (Fig. 1).

Since that time, seismic-detention capabilities of the Lamont-Doherty network have been greatly improved and further supplemented by a dense array of stations located on the northern extension of the Ramapo fault in the vicinity of Consolidated Edison's nuclear-generating plants at Indian Point (Fig. 2)[1].

Aggarwal and Sykes (1978) document a pattern of seismicity (Figs. 1 and 2) that illustrates that numerous low-level events (Nuttli magnitude 1.5 to approximately 3) are occurring throughout a 30 km-wide zone roughly centered on the trace of the Ramapo fault at depths of 0 to about 10 km. Fault-plane solutions (Fig. 2) obtained by them and by Yang and Aggarwal suggest that motion is currently taking place on northeast-striking steeply southeast-dipping surfaces. First-motion studies indicate southeast-to-northwest compression and therefore a reverse-faulting mechanism. They conclude that currect seismicity in the Ramapo zone is being controlled by reactivation of the northeast-striking steeply southeast-dipping faults which make up the predominant structural grain in this area. They further suggest that the Mesozoic border fault, the Ramapo fault, and its northern splays (Fig. 1) are the actual surfaces being reactivated.

The geologic framework of the Ramapo seismic zone, however, is extremely complex. A multitude of faults of different ages have different physical characteristics and contrasting histories. The northeast-trending structural grain of this zone is accompanied by faults of Proterozoic, Paleozoic, Mesozoic and possibly Tertiary and recent age.

Despite the abundant evidence for reactivation of older faults in the Mesozoic, (Ratcliffe, 1971) the Mesozoic and younger faults are not uniformly distributed and do not everywhere coincide with the traces of older faults. Unfortunately, it is not presently possible to produce a tectonic map of this area that accurately shows the distribution of Mesozoic as opposed to older faults. In general, previous studies have not attempted to differentiate Mesozoic faults except where Mesozoic rocks are actually offset. The geologic-tectonic template, therefore, is quite incomplete at present, and any plan to test the hypothesis that geologic structures of Mesozoic age are responsible for current seismicity is severly limited by the lack of appropriate geologic data. Figure 1 shows a new preliminary compilation of fault features.
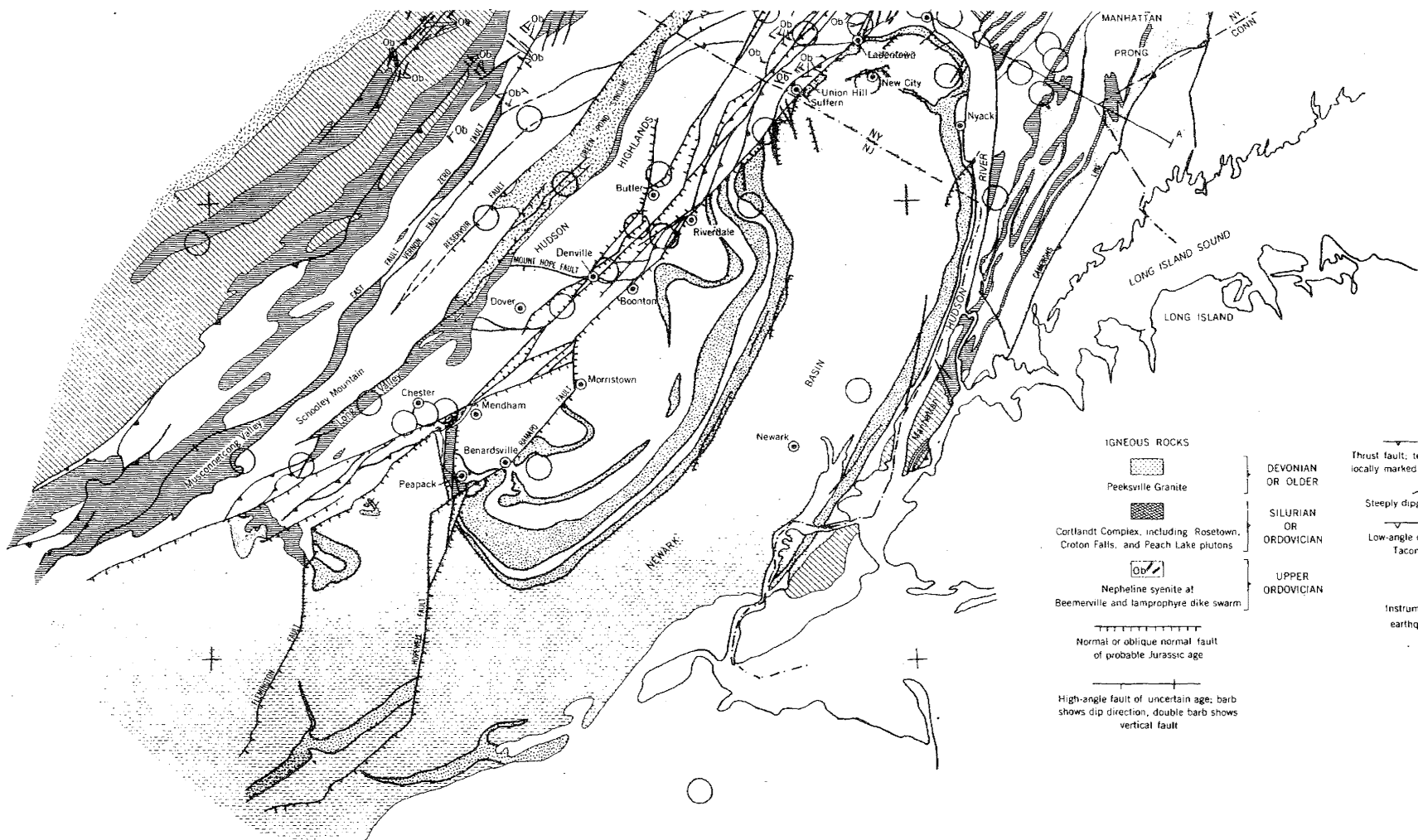
Tectonic framework and fault distribution in northern New Jersey and southeastern New York

Figure 1 shows the distribution of major tectonic features in the Ramapo seismic zone. Two classes of faults are distinguished:

a) faults with associated semiductile fabric in adjacent rocks, and phyllonite or blastomylonite at fault contacts;

b) more brittle faults characterized by discrete breaks and cataclastic fabrics.

This grouping of faults by and large also serves to distinguish thrust faults, largely class (a), from normal or oblique dipslip faults, class (b).

Fig. 1. Preliminary tectonic map of the Reading Prong, northern Newark basin, and Manhattan Prong, showing distribution of "brittle" versus more ductile style fault zones and earthquake epicenters. Compilation uses data of Drake, Lyttle, and Owens (1979), New York State geologic map (Fisher, Isachsen and Rickard, 1971) New York State brittle fracture map (Isachsen and McKendree, 1977), New Jersey Geological Survey maps at 1:62,500, and new data (Ratcliffe, unpub. data) principally along the Ramapo-Canopus fault zone. Locations of U.S. Geological Survey drill holes along the Ramapo fault are identified. This map is preliminary and is likely to be altered substantially as dating of faults and examination of fault-zone materials continue. Line A-A identifies the location of cross section (Fig. 4). Epicenter locations from data of Lamont-Doherty Geological Observatory published in Regional Seismicity Bulletin of the Lamont-Doherty Network, Palisades, N.Y. Horizontal errors are less than 2 km (diameter of circles).

EXPLANATION

Jb
J
JŦ

Jb — Jurassic basalt and diabase
J — Jurassic sedimentary rocks above first lava flow
JŦ — Jurassic and Triassic sedimentary rocks

SEDIMENTARY AND METASEDIMENTARY ROCKS

Devonian and Silurian sedimentary rocks

~~~~ Unconformity ~~~~

] DEVONIAN AND UPPER SILURIAN

Martinsburg Formation
Walloomsac Formation
Balmville[1] and Jacksonburg Limestones

Manhattan Schist, including probable allochthonous units of Cambrian age

Taconic allochthons

] UPPER AND MIDDLE ORDOVICIAN

~~~~ Unconformity ~~~~

Carbonate rocks
Wappinger[1] and Kittatiny Limestones, Inwood Marble, and Hardyston, Poughquag, and Lowerre Quartzites

] ORDOVICIAN AND CAMBRIAN

~~~~ Unconformity ~~~~

Proterozoic Y gneiss and granite of Hudson Highlands, Manhattan Prong, and outliers

] PROTEROZOIC Y

[1]Of New York State usage

0   20 KILOMETERS

MANHATTAN

NY
CONN

PRONG

Ladentown

New City

Ob

Union Hill
Suffern

Nyack

NY
NJ

A

HUDSON RIVER

LONG ISLAND SOUND

LONG ISLAND

Ob

Ob

Ob

Ob

Ob

Ob

Ob

Ob

Butler

HIGHLANDS

Denville

Riverdale

HUDSON

MOUNT HOPE FAULT

Dover

Boonton

Morristown

BASIN

Chester

Mendham

Newark

Benardsville

Peapack

NEWARK

Schooley Mountain

RESERVOIR FAULT

VERNON FAULT

EAST FAULT

ZOO FAULT

Musconetcong Valley

BASIN

IGNEOUS ROCKS

Peeksville Granite
} DEVONIAN OR OLDER

Cortlandt Complex, including Rosetown,
Croton Falls, and Peach Lake plutons
} SILURIAN OR ORDOVICIAN

Ob ⬈ Nepheline syenite at
Beemerville and lamprophyre dike swarm
} UPPER ORDOVICIAN

Normal or oblique normal fault
of probable Jurassic age

High-angle fault of uncertain age; barb
shows dip direction, double barb shows
vertical fault

Thrust fault; teeth on upthrown side;
locally marked by zones of phyllonite

Steeply dipping phyllonite zone

Low-angle overthrust bounding
Taconic allochthons

Instrumentally located
earthquake epicenter

280

On this map, numerous faults of both kinds are present within the Ramapo seismic zone. Definition of faults in New York State is somewhat better than in New Jersey, especially within the Reading Prong, because of recent mapping in a tier of quadrangles extending from the Hudson River west to Greenwood Lake. Recent geologic mapping is somewhat limited in the New Jersey Highlands, and investigations specifically on faults have not been conducted except locally.

A series of previously unrecognized, interconnected Mesozoic faults are now recognized as a result of reconnaissance studies over the past several years. The probable interconnection of the Flemington and Hopewell faults with the Ramapo fault system is worthy of note. Investigations in the Morristown-Bloomingdale to Chester area suggest that individual splays of the main Ramapo fault extend southwestward from a point just north of Morristown to interconnect with the Flemington fault south of Mendham. This zone of faulting coincides with a zone of concentrated earthquake activity in the Bloomingdale-Denville area (Fig. 1).

Faults bounding the Green Pond syncline are interpreted to be Triassic and Jurassic, although reactivation of older faults is likely, especially on the Reservoir fault. The Tuxedo Lake valley, however, is bordered by abundantly block-faulted rocks that have zeolite-chlorite mineralization and irregular wear grooves typical of Mesozoic faults. These rocks almost certainly mark a zone of Jurassic faulting. A similar zone extends northeastward to Sebago Lake from the Sloatsburg area.

The Ramapo fault itself extends from the Peapack-Gladstone area northeastward to Thiells, N.Y., where it bifurcates into the Thiells and Mott Farm Road faults (Figs. 8, 9). A possible zone of Jurassic faulting may extend through Timp Pass, although the bulk of the fault fabrics here are mylonite associated with class B faults of probable Paleozoic age and Proterozoic age.

North of the Hudson River, evidence for Mesozoic faulting along the Ramapo N. 40° E. trend is absent, but a zone of Mesozoic faulting does extend northward along the Hudson River. The tracing of these Mesozoic faults northward is uncertain.

The Peekskill fault, which forms the boundary of the Manhattan Prong, is largely a Paleozoic fault, although some Triassic and Jurassic reactivation is possible with a south-side-down sense of motion.

Mesozoic fractures show characteristics of brittle surface breakage such as wear grooves, irregular indentations, and polished surfaces that are indicative of stick-slip behavior commonly ascribed to movements that produce earthquakes. Therefore, it may be logical to assume that classes of faults showing these features at the surface in a seismic area are the faults most likely associated with the current activity. The obverse argument is that healed, more ductile faults that do not show evidence of movement in an earthquake-generating mode are probably not responsible for producing present-day earthquakes.

Acceptance of this premise has profound significance because it suggests that present-day seismicity in crystalline terranes such as the northeastern United States should be occurring in tectonic areas only where brittle fractures have in the proper attitude for reactivation by present stress fields.

My present feeling is that we have not yet demonstrated either from experiment, theory, or empirical observation that the premise restricting seismic activity to surface brittle fracture zones is at all valid. The Ramapo seismic zone is the best locality, but perhaps the most complex area in the eastern U.S. in which to empirically test this premise.

Semiductile shear zones, expressed by phyllonite or diapthoritic phyllonite-blastomylonite are common throughout the Proterozoic rocks of the Hudson Highlands. A zone of especially intense concentration of these faults is located in the Canopus zone north of Peekskill. Detailed mapping has allowed tracing of these faults northwestward toward Carmel, N.Y., and southwestward to near Boonton, where ductile shear zones are truncated by the Ramapo fault. Throughout this belt, metamorphic mineral fabrics found in fault zones indicate progressive increase in grade northeastward in sympathy with increasing Ordovician isograds. This prograde character of the retrogressive shear zone minerals in these faults suggests that these faults are Ordovician or older.

Independent evidence for the age of these sheared rocks comes from the age of igneous rocks that crosscut or intrude along these faults. Igneous plutonic rocks of the Rosetown outlier of the Corlandt Complex and a swarm of lamprophyre, andesite and rhyodacite dikes intrude across the fault zones that include rocks as young as Middle Ordovician. K-Ar, $^{40}Ar/^{30}Ar$, and Rb/Sr age determination indicate that these dikes and plutonic rocks are roughly the same age as the regional Taconic dynamothermal metamorphism at 440-460 m.a. or Taconic (Dallmeyer, 1975; Dallmeyer and Sutter, 1976). A swarm of dikes extends S. 80° W. from Cortlandt to Beemerville, N.J., where the strongly alkalic "Beemerville" nepheline syenite of Ordovician age crops out. The uniqueness of the structural grain has just recently been recognized as a result of study of the dike systems in the highlands of New Jersey and New York and is of regional importance.

These semiductile shear zones are found west of the Ramapo border fault in New Jersey as far south as the Gladstone-Peapack area and invariably show steep southeast-dipping attitudes. To the west in the Reading Prong, shear zones are less well known, but many dip more gently southeast and appear to form at the soles of overthrust that carry Proterozoic Y rocks northwestward over Paleozoic strata.

Without doubt, these major semiductile fault zones are present in the basement rocks beneath the Mesozoic Newark basin. I believe that these faults are major tectonic features of Ordovician and Proterozoic age that have localized fault activity throughout geologic time. Current seismic activity may be more strongly controlled by the presence of these through-going crustal structures than it is by the more superficial Mesozoic faults.

On this trip, we will examine the cataclastic-mylonitic rocks associated with Mesozoic, Paleozoic, and Proterozoic faults throughout the Ramapo seismic zone. Special attention will be given to the complex geologic history that produced the tectonic grain in Proterozoic Y and Cambrian and Ordovician rocks up-plunge from the Newark basin in the Hudson Highlands. The role that these faults played in the Taconic orogeny will be stressed. I hope to demonstrate by examination of several exposures the spatial association of Paleozoic phyllonite zones (that encorporate slivers of Cambrian and Ordovician metasedimentary rocks) with later zones of Mesozoic reactivation.

Fault Reactivation: structural control of Mesozoic faults by older Tectonic grain and current seismicity

Semiductile shear zones such as the Canopus faults, Thiells, and unnamed shear zones subparallel to the Ramapo fault, dip steeply into the crystalline basement of the Newark basin. The N. 40° E. tectonic grain along which these faults trend, was formed in the "Grenville" deformation approximately 1 b.y. ago. Subsequent reactivation in the Ordovician produced right-oblique thrust faults and intense zones of phyllonitization.

Field studies and results of drill coring of the Triassic border fault (Ramapo fault) have shown that these more ductile zones are not manifestations of Triassic and Jurassic cataclasis, but metamorphic mylonites formed under greenshist-grade regional metamorphism. Results of isotopic studies also support the old age of these shear zones. Figure 3 shows the schematic relationship of depth of formation and age of some of these features.

The steeply dipping shear zones served to localized Triassic and Jurassic faulting along the Canopus trend.

Cataclasis associated with these faults is characteristically brittle and has resulted in gouge and cataclasite.

A generalized cross section across the Reading and Manhattan Prongs (Fig. 4) shows the general steepening of that phyllonite shear zone in the vicinity of the Ramapo fault zone. Earthquake hypocenters (Fig. 4) in the vicinity of this section tend to be deeper in the southeast than in the northwest. Fault-plane solutions for events as deep as 10 km within the Ramapo fault zone indicate steep dips of 60° - 70° coinciding with the attitude of both the ductile shear zones and the Triassic and Jurassic faults (Fig. 2). Current seismicity appears to be controlled by attitude and distribution of the older shear zones, that in turn have localized Mesozoic faulting.

The current stress sytem requires southeast-northwest compression (Aggarwal and Sykes, 1978). Detailed examination of drill cores of the actual Ramapo fault have revealed no evidence of reactivation as a thrust fault along the actual Ramapo fault surface. In addition, no data has yet been discovered of offset glacially polished surfaces or of surficial deposits where they have been trenched across the Ramapo fault. Studies of surficial deposits near the fault trace are in progress.

Regional geology and major tectonic problems in the Reading Prong

Proterozoic Y rocks form the basement of the Reading-Hudson Highlands and of the Manhattan Prong. These terrains are part of the 1 b.y. old North American basement consolidated prior to onset of Appalachian tectonics that began with late Proterozoic rifting and initiation of oceanic spreading of the Iapetus ocean. Cover rocks of these areas are also distinctly North American and consist of Lower Cambrian through Middle Ordovician shelf and exogeosynclinal sediments formed on the foundered edge of the North American continent.

Basement gneisses of charnokitic affinities crop out in the Hudson Highlands west to the Canopus fault zone. Available geochronologic data suggest that regional dynamothermal metamorphism and plutonism may have occurred between 1139 ± 10 m.y. ago and 914 ± 12 m.y. ago based on Rb/Sr ages for metamorphic rocks, syntectonic and late tectonic granites (Helenek and Mose, 1976). Polyphase folding and plutonism are widely recognized by Helenek and Murray (in Hall and others, 1975).

A major tectonic zone of highly faulted rock, the Canopus fault zone (Ratcliffe, 1971) (Fig. 1) effectively separates the western Highlands block from the eastern
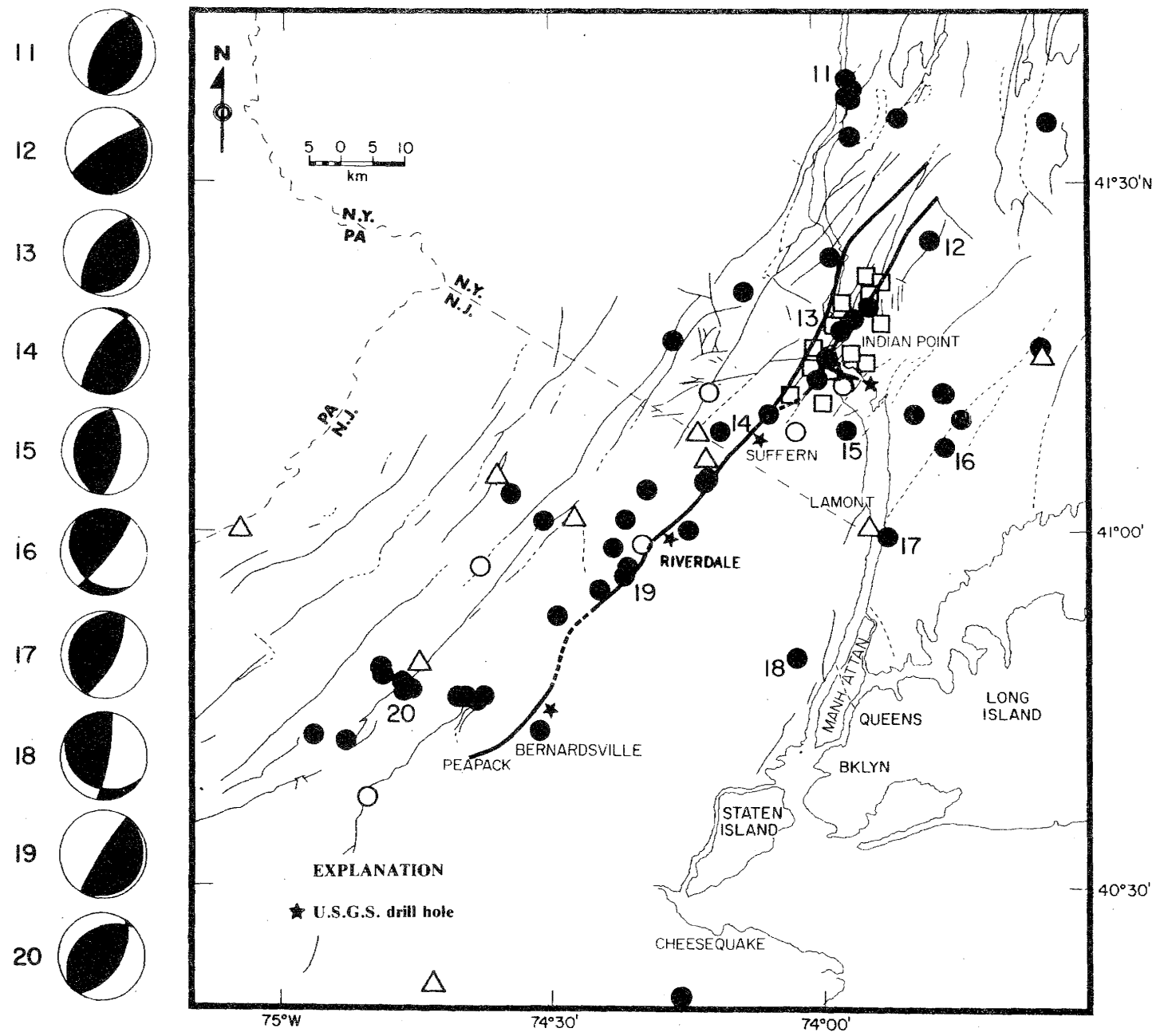
Fig. 2. Location of earthquake epicenters and fault-plane solutions for Ramapo seismic zone reproduced from Yang and Aggarwal [4]. Location of U.S. Geological Survey drill holes along Ramapo fault are shown. Stereograms show upper hemisphere projections for individual fault-plane solutions identified on map. Triangles show location of Lamont-Doherty stations, small boxes Consolidated Edison network. Open circles, events 1951-1972; closed circles, events 1973-1979.

Diagrammatic representation of fault episodes and fault products in the Ramapo fracture zone through time.
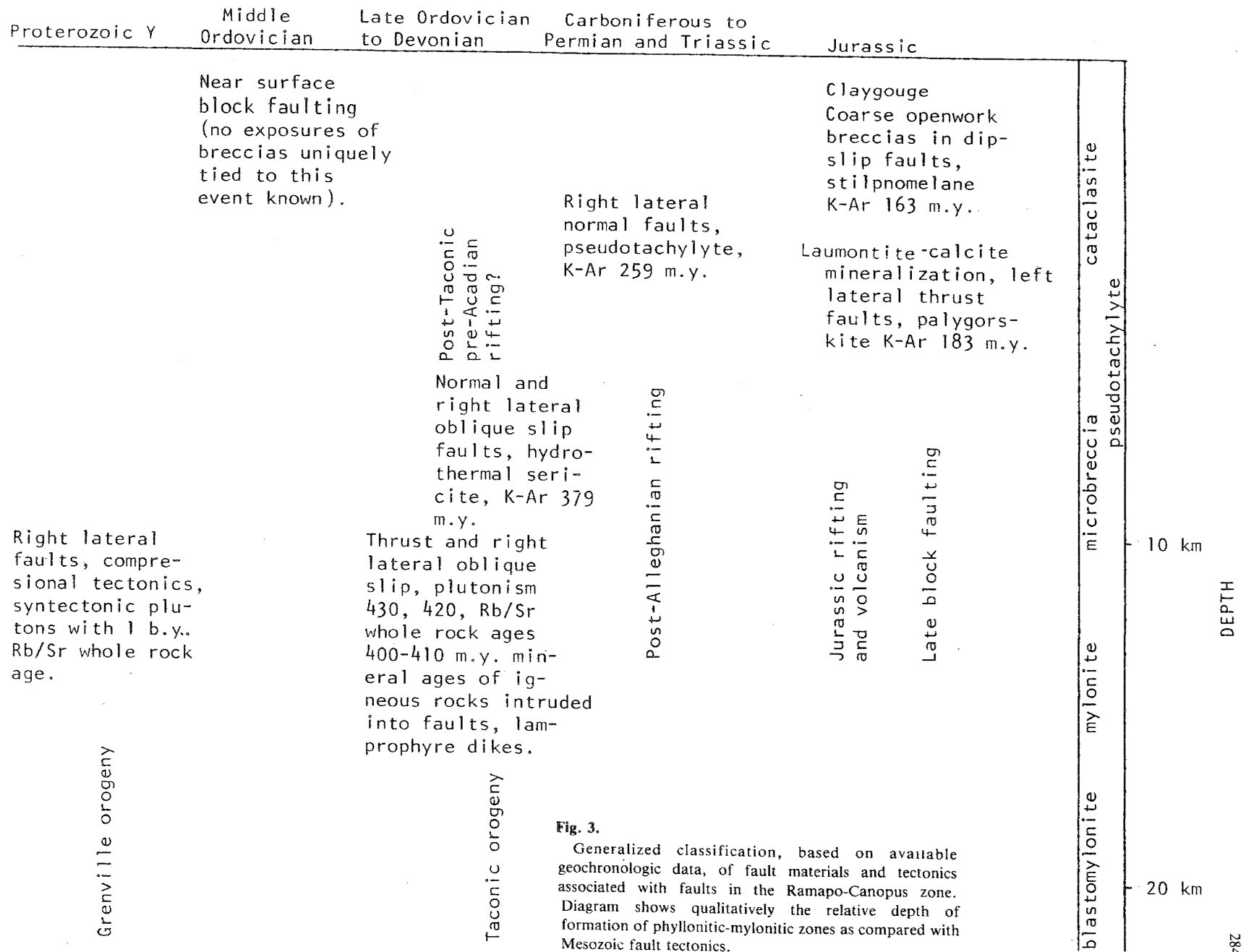
Proterozoic Y	Middle Ordovician	Late Ordovician to Devonian	Carboniferous to Permian and Triassic	Jurassic

Near surface
block faulting
(no exposures of
breccias uniquely
tied to this
event known).

Claygouge
Coarse openwork
breccias in dip-
slip faults,
stilpnomelane
K-Ar 163 m.y.

Right lateral
normal faults,
pseudotachylyte,
K-Ar 259 m.y.

Laumontite-calcite
mineralization, left
lateral thrust
faults, palygors-
kite K-Ar 183 m.y.

Post-Taconic pre-Acadian rifting?

Normal and
right lateral
oblique slip
faults, hydro-
thermal seri-
cite, K-Ar 379
m.y.

Post-Alleghanian rifting

Thrust and right
lateral oblique
slip, plutonism
430, 420, Rb/Sr
whole rock ages
400-410 m.y. min-
eral ages of ig-
neous rocks intruded
into faults, lam-
prophyre dikes.

Right lateral
faults, compre-
sional tectonics,
syntectonic plu-
tons with 1 b.y.
Rb/Sr whole rock
age.

Jurassic rifting and volcanism

Late block faulting

Grenville orogeny

Taconic orogeny

cataclasite

pseudotachylyte

microbreccia

mylonite

blastomylonite

DEPTH

— 10 km

— 20 km

Fig. 3.

Generalized classification, based on available
geochronologic data, of fault materials and tectonics
associated with faults in the Ramapo-Canopus zone.
Diagram shows qualitatively the relative depth of
formation of phyllonitic-mylonitic zones as compared with
Mesozoic fault tectonics.

Hudson Highlands. Hall and others (1975) have suggested that Proterozoic Y rocks east of this fault zone are unlike rocks of the western Highlands block. The Canopus zone has been the locus of fault activity in the Proterozoic, Ordovician, and possible Triassic (Ratcliffe, 1971) and plutonic rocks of the Canopus pluton dated at about 1070 m.y. by Armstrong (Ratcliffe and others, 1972) are syntectonically deformed in the fault zone. The lack of correspondence of Proterozoic rocks across this zone led to the suggestion that the two terrains are of considerably different parentage and that the eastern block may be allochthonous with respect to the main Reading Prong (Hall and others, 1975). This difference is also expressed in differing aeromagnetic patterns for these two areas of basement. West of the fault zone, the aeromagnetic patterns are characterized by linear, high-amplitude anomalies. East of the fault, the patterns are broad, low-amplitude features without strong linear pattern (Harwood and Zeitz, 1974).

The linear magnetic belt characteristic of the Beacon-Copake anomaly west of the Canopus zone is approximately 25 km wide. The western boundary of this zone is marked by exposure of biotite-rich paragneiss amphibolite, calc-silicate rocks, and associated magnetite deposits (Dodd, 1965). The eastern boundary is also marked by northeast-trending linear belts of magnetite deposits, the Sprout Brook, Canopus Hill "ore ranges"

of Colony (1921). The internal structure of this zone is dominated by northeast-trending limbs of steep isoclinal folds in which the distribution of steeply dipping highly magnetic calc-silicate and paragneiss units are adjacent to weakly magnetic granitic and leuocratic rocks. The distinctive aeromagnetic pattern, therefore, appears to result from the presence of near-vertical belts of highly magnetic rocks on the limbs of regional folds. At the Canopus zone the structural style in Proterozoic rocks changes from one of steeply dipping linear belts of Proterozoic rocks to one of a swirled pattern of more open folding with shallow northeastern plunges. East of the Canopus belt broad aeromagnetic anomalies greater than 1300 gammas are associated with amphibolite and calc-silicate rocks locally bearing magnetite deposits as at Brewster, Mahopac, and Sprout Brook belts (Colony, 1921).

This leads to the conclusion that the linear aeromagnetic pattern described by Harwood and Zeitz (1974) may result largely in part from the configuration of magnetic rock units rather than from an inherent difference in the rocks. The magnetic grain or signature of the western Highlands was produced by the structural imprint of Proterozoic Y age, which terminates at the Canopus zone. West of this zone, Proterozoic Y rocks contain N. 40° E.-trending isoclinal folds that have steep axial surfaces and vertical limbs. In the Canopus zone, superposition of strain-slip folds and shear zones
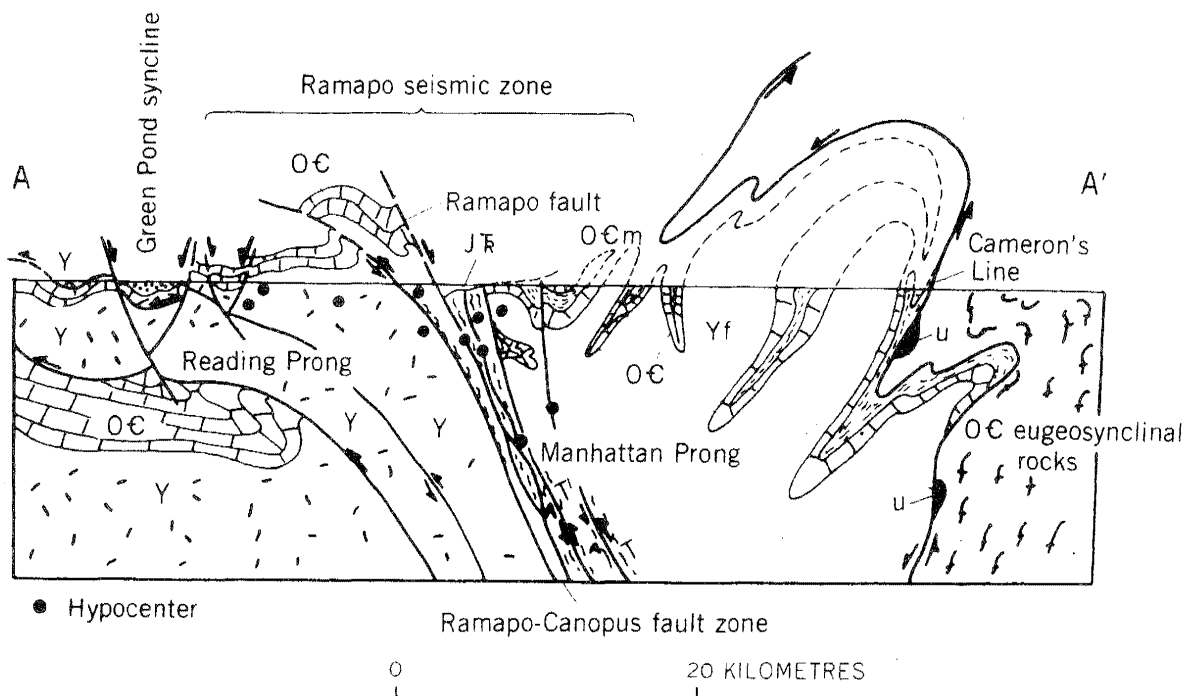

Fig. 4.   1:1 cross section across the Reading and Manhattan Prongs showing inferred deeper crustal structure and approximate hypocenters for earthquakes within the Ramapo seismic zone near line of section. Note increasing depth of hypocenters near ductile Ramapo-Canopus zone. Earthquakes as deep as 10km yield fault-plane solution indicating movement on steeply southeast-dipping faults in Ramapo-Canopus zone.
Y = Proterozoic rocks; Yf = Fordham Gneiss; OЄ = Ordovician and Cambrian miogeoclinal rocks; OЄm = Manhattan Schist; u -ultramafic rocks east of Cameron's Line. See figure 1 for location of section.

disrupt this older "Grenville" structure. Some evidence suggests that folds of Proterozoic Y age east of the Canopus zone are oriented differently and represent a different tectonic belt east of a Proterozoic shear zone. The difference in tectonic style and in consequent aeromagnetic patterns is probably the result of juxtaposition of two structural domains in Proterozoic time.

An alternate hypothesis is that the rocks east of the Canopus zone have a different structural style because of intense Paleozoic overprinting. The problem is not easily resolved, and most probably Proterozoic and Paleozoic tectonism are involved and the eastern Highlands undoubtedly do contain a complicated composite structural fabric. Figure 16, A, B, C shows schematically the structural evolution of the Ramapo-Canopus fault zone.

A major unresolved tectonic problem is the nature and extent of overthrusting of basement rocks of the Reading Prong. Field workers in the Hudson Highlands regard the northern part of the Reading Prong as mantled by a continuous shelf cover on the western edge with limited thrust faulting.

Two recent articles by Dallmeyer (1974) and Harwood and Zeitz (1974) have dealt with structural interpretations of the northern end of the Reading Prong. Their results appear to confirm the basic conclusion of field workers in this area that the northern end of the Reading Prong from Beacon northeastward may not be allochthonous in the sense proposed by Isachsen (1964). Isachsen advocated total allochthony of the Reading Prong with respect to the Paleozoic shelf-sequence rocks to the northwest and to the Manhattan Prong to the southeast.

Harwood and Zeitz (1974) have shown that linear magnetic patterns in exposed Proterozoic rocks project N. 30° - 40° E. from Beacon, N.Y., to Copake, N.Y. (Beacon-Copake magnetic anomaly), beneath overlying Cambrian and Ordovician cover rocks. This observation suggests that basement rocks of the Reading Prong are not allochthonous with respect to the cover rocks of the Hudson River Valley area.

Detail mapping of the Ramapo-Canapos zone and of the contact between the Hudson Highlands and the Manhattan Prong (Ratcliffe, 1971 and unpub. data) reveals that no trailing edge is preserved near this southern and eastern border in the Proterozoic rocks. Instead, structural data suggest that faults within crystalline core of Reading Prong steepen as this contact is approached. I prefer the interpretation, shown schematically in figure 4, that the Reading Prong, at the latitude of New York is dominated by deeply rooted

wedges of basement rock thrust westward and southwestward during Taconic deformation.

Mesozoic faults of the Ramapo fault zone

The Ramapo fault forms the western border of the Newark basin (Fig. 1), and extends as a discrete structural feature from Ladentown, N.Y., south to Peapack, N.J. North of Ladentown, the fault may bifurcate into two branches, one trending N. 20° E. and the other N. 60° E. connecting northeastward with the Thiells fault, although this connection is not verified. The projection of the Ramapo fault northward into the Hudson Highlands is complex. One arm, the Mott Farm Road fault, extends northeastward and rejoins the main border fault north of Tomkins Cove, N.Y. Northeast of Tomkins Cove, Mesozoic faults are not abundant, although a zone of typical Mesozoic faults extend northward along the Hudson River at least as far as Cold Spring, N.Y.

South of Suffern, N.Y., the Ramapo is moderately straight until the Pompton Plains area where splays and a series of en echelon faults passes into the Hudson Highlands. Major faults, previously unrecognized, trend southwestward from Morristown, N.J., toward the Denville-Chester area and may connect to the south with the Flemington fault.

The Ramapo fault is easily recognized as far south as Bernardsville, N.J. South of Bernardsville the Ramapo fault appears to branch into a series of more southerly directed splays and to connect with the Hopewell fault. The likelihood of this connection has not been recognized until recently (Adams, 1980; Manspeizer, personal commun., 1980; Olsen, personal commun., 1980). Mapping in the Gladstone area suggests that previously drawn maps showing the Ramapo curving westward to join with the Flemington fault appear incorrect on the basis of my remapping of the Gladstone area.

The major pattern of Mesozoic faults is shown on figure 1. All cores examined show evidence of right-lateral slip which produced minor folds and dragging of older cataclastic fabrics.

Fault breccia, cataclasite, and gouge predominate in the Ramapo drill cores. Cataclasite with a strong fluxion structure is present and gives the fault rock a mylonitic fabric. Neomineralization consists of chlorite, calcite, and laumontite.

Magnitude and movement history of the Ramapo fault

The Ramapo fault offsets rocks as young as middle Early Jurassic (Sinemurian) in the vicinity of Riverdale, N.J. (Boonton Formation of Olsen, this publication).

From Ladenton, N.Y. to Peapack, N.J., the fault truncates approximately 1400 m of basalt and sedimentary rock on the western limb of the Watchung syncline, on the basis of thickness estimates of Olsen (this publication). If the fault connects northward with the Thiells fault, stratigraphic throw of approximately 4 km is possible if we assume that the sedimentary deposits do not thin northwestward. Alternately, most of the movement on the Ramapo fault could have been taken upon its northern extension, the Mott Farm Road fault, and the 1400 m of probable stratigraphic separation cited

above could be used as an estimate. The actual displacement of the Ramapo fault is unknown. Folding of the Triassic strata in the Watchung syncline prodated faulting or was produced by drag folding during faulting. Data do not appear to support the concept that deeper strata in the northern end of the Newark basin have undergone greater rotation than younger deposits, an argument used to support syndepositional faulting.

I have examined the outcropping fault fabric associated with the Ramapo fault over its entire length

EXPLANATION

Jurassic and Triassic rocks
of Newark basin

Jb1, 2, 3, 4– Lava flows
Jc – Border conglomerate and gneiss boulder
   conglomerate
J – Sedimentary rocks between lava flows 1
   and 2, 2 and 3, and above 3
J $\bar{\mathrm{R}}$ – Sedimentary rocks

Black phyllite

Poughquag Quartzite

Yhg – Hornblende granite gneiss
Ys – Rusty sillimanite gneiss
Ya – Amphibolite
Yps – Diopsidic gneiss
Yag – Amphibolitic gneiss
Ysk – Calcite marble and calc silicate
Yhy – Hyperthene plagioclase gneiss
Yb – Mylonitic quartzitic paragneiss
Ya – Undifferentiated gneiss

Earthquake epicenter;
bars represent estimated horizontal error

High-angle fault with brittle surface features;
ball shows dip; arrows show sense of strike
slip component; D, downthrown block; U,
upthrown block

Phyllonitic shear zone

Core drill site

STOP 1
Field trip stop

Axial trace
Proterozoic y fold

Syncline and anticline in
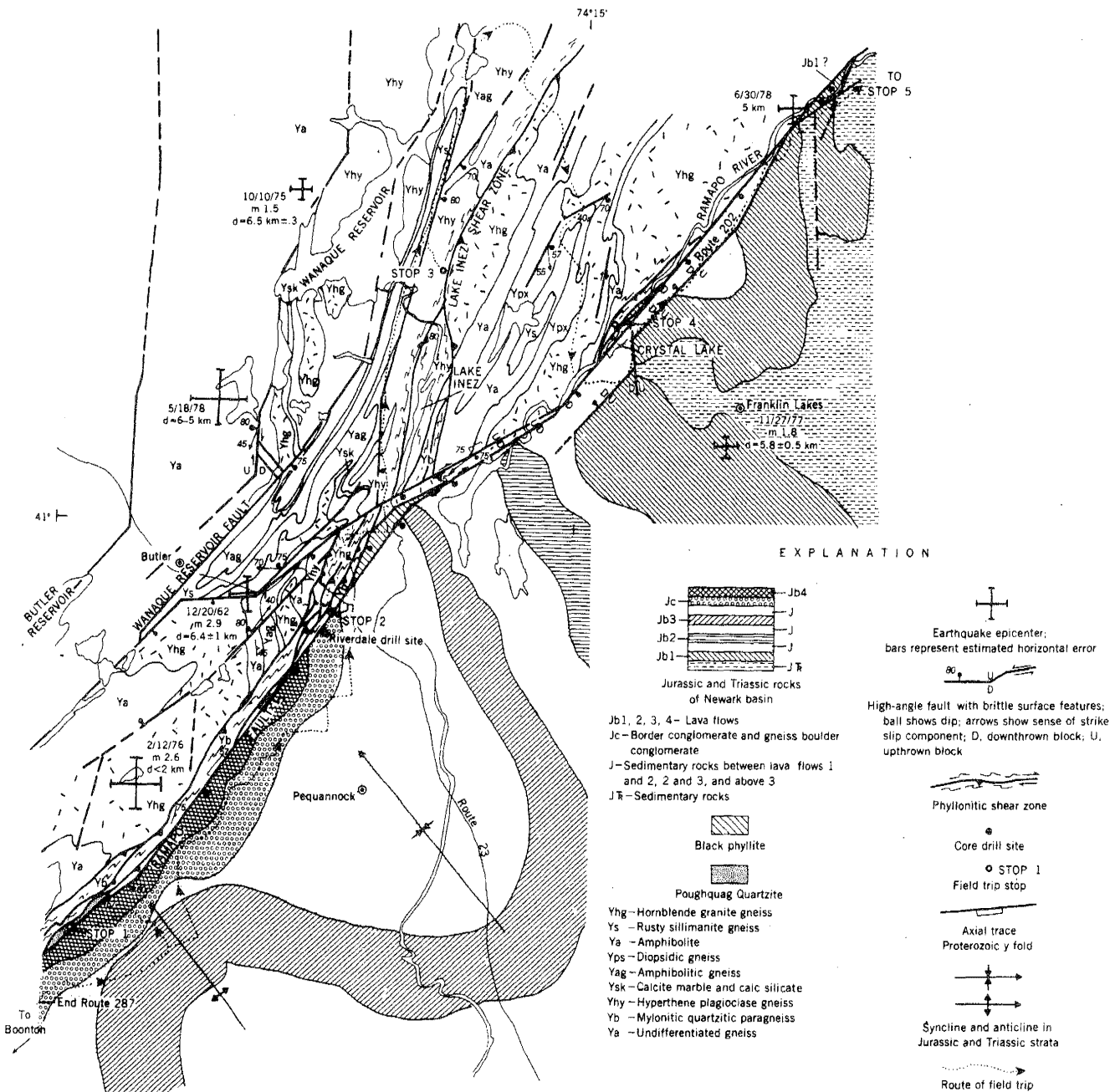Jurassic and Triassic strata

Route of field trip

Fig. 5.   Generalized geologic map of the Ramapo fault between Boonton, N.J., and Suffern, N.Y., showing distribution of semiductile shear zones with associated slivers of Paleozoic rocks and more brittle faults of probable Mesozoic age. Location of earthquake epicenters are shown. Geology of fault zone based on new data (Ratcliffe, unpub. data). Stop locations and location of Riverdale drill core figures 6 and 7 are shown. North of Riverdale, a splay of the Ramapo fault offsets Proterozoic structure and phyllonite zones 1.5 km in a right-lateral sense.

and examined continuous cores obtained at four major sites distributed along its length (Fig. 2).

The results of all these observations are reasonably consistent. Steep conjugate normal-fault fracture patterns dominate in the footwall block with extensive fracturing limited to within 100-200 m of the fault. Rusty weathering, chlorite-coated and slickensided and grooved surfaces are common. Calcite and laumonite fill extension fractures. Evidence for multiple movement with a significant component oblique slip is common. The primary movement plan for the border fault appears to be right-oblique normal movement on southwest-dipping surfaces and left-oblique movement on northwest-dipping surfaces.

Attitude of the Ramapo fault

The results of drill core information from three drill sites along the length of the Ramapo fault are shown in figures 6, 10, and 13. The dip of the fault is variable: 70° SE. at Stony Point, 55° SE. north of Suffern (Sky Meadow site), 50° - 55° at Riverdale, 50° - 45° at Bernardsville. At each of these localities, the actual fault contact is marked in drill cores by nonhealed unconsolidated rock gouge 1-5 cm thick. Details of some of the actual contacts are shown in figures 5, 7, and 11.

The footwall block at these localities is predominantly hornblende granite gneiss in the north and dioritic or amphibolitic gneiss at the two southern sites. Examination of fracture patterns, and slickensides, and micro-offsets indicate a predominant, down-to-the-southeast sense of movement with evidence for both right-lateral and left-lateral movement. The dominant sense of movement is right oblique normal faulting. Folding and plication of fluxion banded cataclasite is commonly found immediately above the fault attesting to some reactivation. The drag sense of deflected fluxion banding is consistent with right-oblique normal faulting.

Evidence for syndepositional faulting

Carlston (1946) and previous writers have suggested that active faulting occurred during sedimentation. The arguments that favor this are:

1 . Coarse border conglomerates and fans localized near border fault.

2 . Very local sources of material in basin suggesting high local relief.

3 . Fragments of pillow basalt in the fanglomerate suggesting that lava flows overstepped the basin

and were fed back into basin as a result of renewed faulting (seen in conglomerates below the two higher lava flows).

4 . Fragments of mylonitic or cataclastic rocks of footwall in the border conglomerate (these have been seen at Boonton, Ladentown, and Tomkins Cove).

5 . Large blocks of cataclastic rock in fan deposits (to be seen at Union Hill, Stop 6).

6 . Progressive unroofing of highlands block as recorded by abundant detritus of Proterozoic Y age in the youngest conglomerates of the basin. (Proterozoic gneiss fragments are abundant in the youngest deposits but rare in Upper Triassic rocks).

7 . Relationship of the lava flows at Ladentown to underlying folded rocks. The Ladentown lava flows (Stop 7) show evidence of having flowed along a stream channel incised into previously folded Triassic strata. The lava may have ponded against the fault escarpment.

Although all of these arguments do suggest fault activity during sedimentation, the magnitude of this activity is quite uncertain. It is my feeling that estimates of probable displacement on the border fault are greatly exaggerated and are not more than 500 m along the northward extension of this fault into the Hudson Highlands near Stony Point and on the Mott Farm Road faults. These estimates are based on correlation of Proterozoic and Paleozoic structures across Mesozoic faults at the north end of the basin where the possibility of large (greater than 500 m) displacements here on Mesozoic faults are precluded.

Examination of the clasts found in the border conglomerate suggest that extremely local sources existed in or near the border fault in Sinemurian and older time.

1 . At Riverdale, fragments of phyllonitic hornblende granite gneiss, veined with epidote, are traceable to outcrops several hundred meters west of the conglomerate and must have been very locally derived (Stop 2).

2 . At Stony Point, fragments of Cambrian quartzite traceable to local outcrops 400 m southwest are found in this fanglomerate at Stop 10.

3 . At the north end of the basin, distinctive clasts of hornfelsed Manhattan Schist from the contact aureole of the Corlandt Complex less than
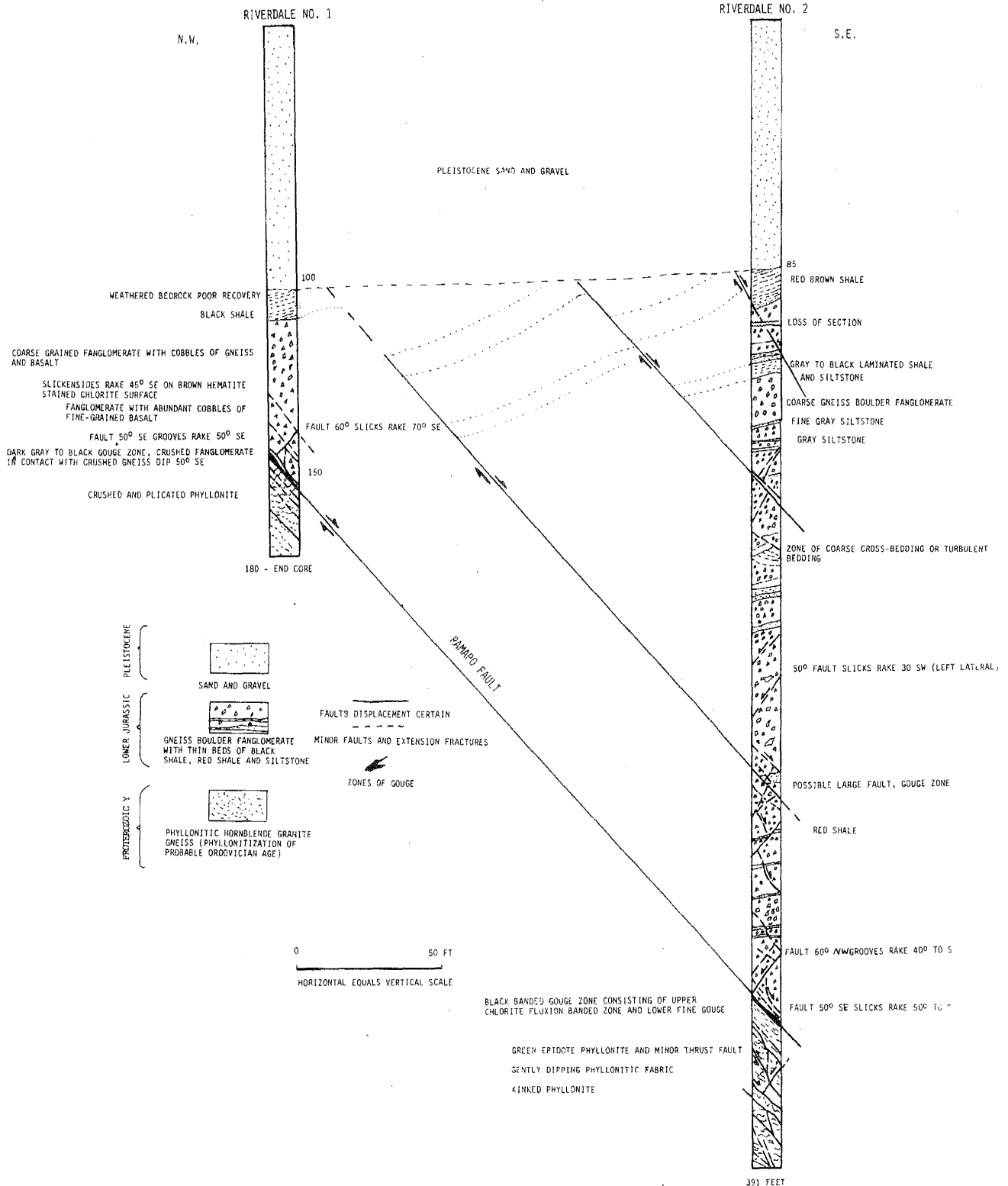
Fig. 6.   Cross section showing attitude of Ramapo fault at Riverdale drill site Two continuous cores penetrated the fault between Jurassic fanglomerate and phyllonitic gneiss of footwall.
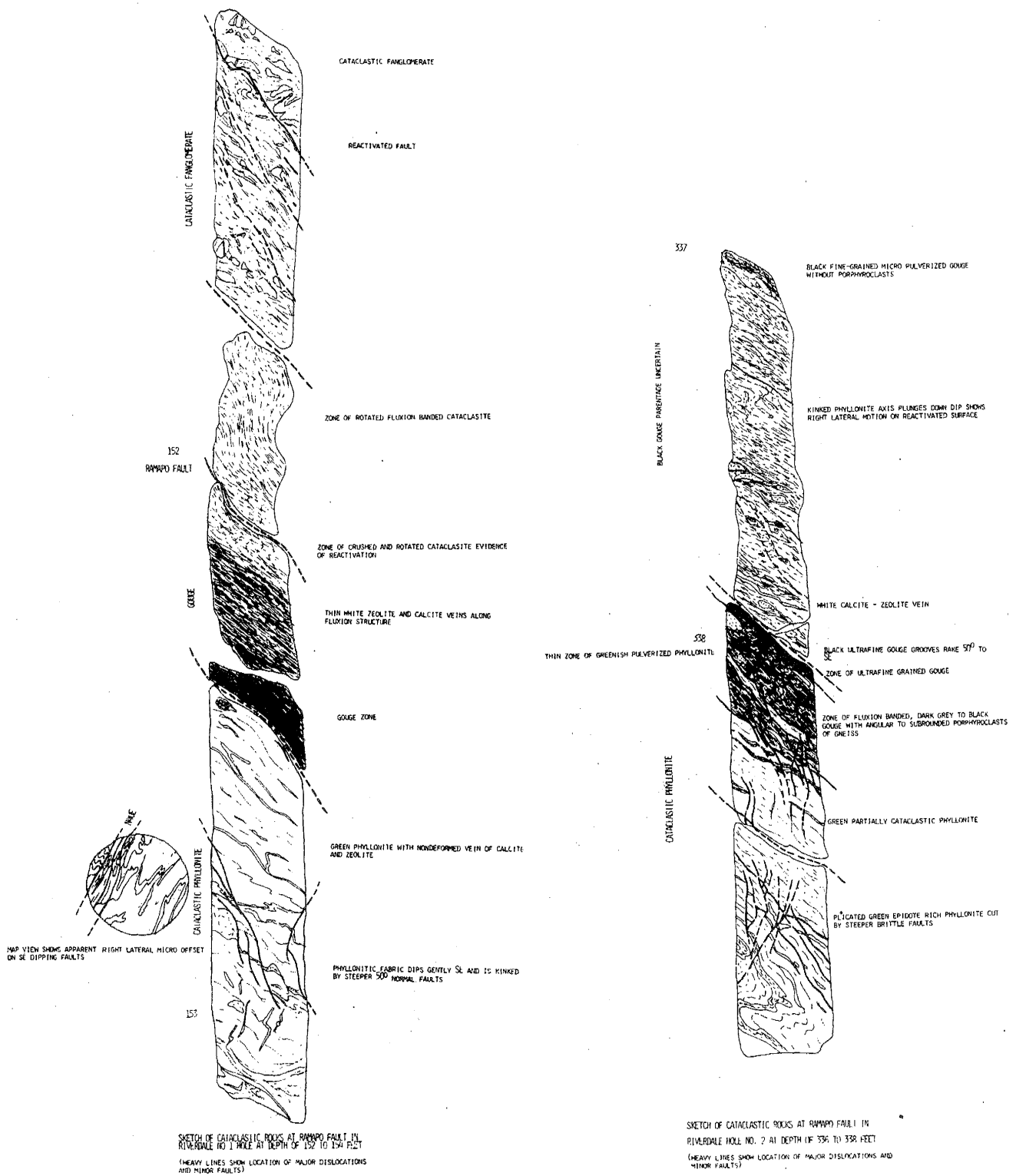
CATACLASTIC FANGLOMERATE

REACTIVATED FAULT

ZONE OF ROTATED FLUXION BANDED CATACLASITE

ZONE OF CRUSHED AND ROTATED CATACLASITE EVIDENCE OF REACTIVATION

THIN WHITE ZEOLITE AND CALCITE VEINS ALONG FLUXION STRUCTURE

GOUGE ZONE

GREEN PHYLLONITE WITH NONDEFORMED VEIN OF CALCITE AND ZEOLITE

PHYLLONITIC FABRIC DIPS GENTLY SE AND IS KINKED BY STEEPER 50° NORMAL FAULTS

MAP VIEW SHOWS APPARENT RIGHT LATERAL MICRO OFFSET ON SE DIPPING FAULTS

152 RAMAPO FAULT

153

SKETCH OF CATACLASTIC ROCKS AT RAMAPO FAULT IN RIVERDALE NO 1 HOLE AT DEPTH OF 152 TO 154 FEET
(HEAVY LINES SHOW LOCATION OF MAJOR DISLOCATIONS AND MINOR FAULTS)

337

BLACK FINE-GRAINED MICRO PULVERIZED GOUGE WITHOUT PORPHYROCLASTS

KINKED PHYLLONITE AXIS PLUNGES DOWN DIP SHOWS RIGHT LATERAL MOTION ON REACTIVATED SURFACE

WHITE CALCITE - ZEOLITE VEIN

BLACK ULTRAFINE GOUGE GROOVES RAKE 50° TO SE

ZONE OF ULTRAFINE GRAINED GOUGE

ZONE OF FLUXION BANDED, DARK GREY TO BLACK GOUGE WITH ANGULAR TO SUBROUNDED PORPHYROCLASTS OF GNEISS

GREEN PARTIALLY CATACLASTIC PHYLLONITE

PLICATED GREEN EPIDOTE RICH PHYLLONITE CUT BY STEEPER BRITTLE FAULTS

338 THIN ZONE OF GREENISH PULVERIZED PHYLLONITE

SKETCH OF CATACLASTIC ROCKS AT RAMAPO FAULT IN RIVERDALE HOLE NO. 2 AT DEPTH OF 336 TO 338 FEET
(HEAVY LINES SHOW LOCATION OF MAJOR DISLOCATIONS AND MINOR FAULTS)

Fig. 7. Detailed sketches of cataclastic rocks from Ramapo fault at Riverdale drill site showing physical character of rock materials. Phyllonite penetrated below fault is material cropping out at ledges at Riverdale, Stop 2, and is traceable northward to next stop at Wanaque. The phyllonite is disrupted by post-Sinemurian faulting. The last recorded movement was of a normal kind. No evidence of reactivation as a reverse fault is seen. Cores are 2 in. in diameter.
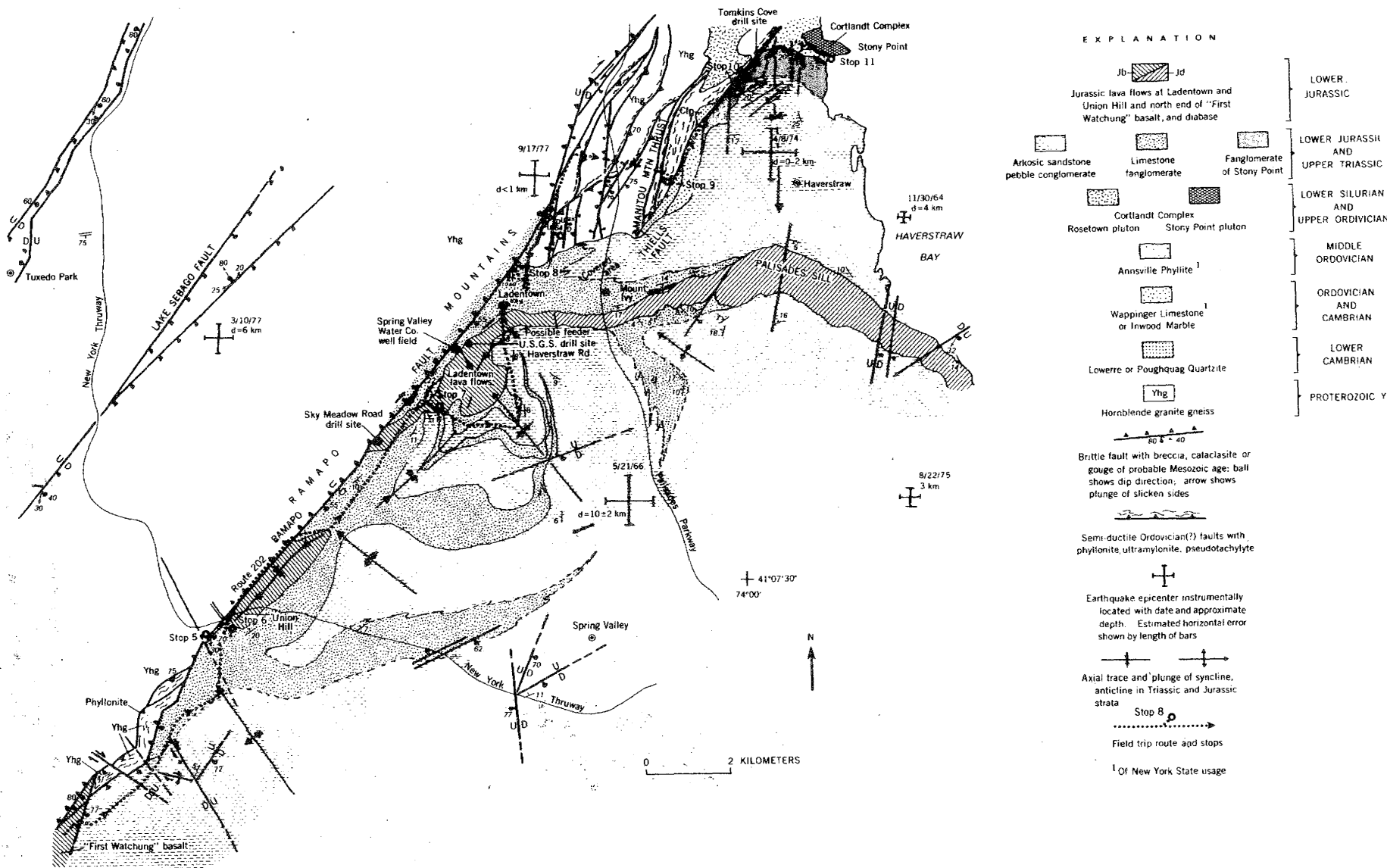
E X P L A N A T I O N

Jb [///] Jd

Jurassic lava flows at Ladentown and
Union Hill and north end of "First
Watchung" basalt, and diabase

LOWER
JURASSIC

Arkosic sandstone
pebble conglomerate

Limestone
fanglomerate

Fanglomerate
of Stony Point

LOWER JURASSIC
AND
UPPER TRIASSIC

Cortlandt Complex
Rosetown pluton   Stony Point pluton

LOWER SILURIAN
AND
UPPER ORDIVICIAN

Annsville Phyllite [1]

MIDDLE
ORDOVICIAN

Wappinger Limestone [1]
or Inwood Marble

ORDOVICIAN
AND
CAMBRIAN

Lowerre or Poughquag Quartzite

LOWER
CAMBRIAN

Yhg

Hornblende granite gneiss

PROTEROZOIC Y

Brittle fault with breccia, cataclasite or
gouge of probable Mesozoic age; ball
shows dip direction; arrow shows
plunge of slicken sides

Semi-ductile Ordovician(?) faults with
phyllonite, ultramylonite, pseudotachylyte

Earthquake epicenter instrumentally
located with date and approximate
depth. Estimated horizontal error
shown by length of bars

Axial trace and plunge of syncline,
anticline in Triassic and Jurassic
strata

Stop 8

Field trip route and stops

[1] Of New York State usage

Fig. 8. Generalized geologic map of the northern part of the Newark basin showing probable physical connection of Palisades sill with lava flows of Ladentown and the apparent truncation of folded Triassic and Jurassic rocks by the flows. Brittle faults within and adjacent to basin record both right-lateral and left-lateral movements with northwest-trending faults the latest. Two sets of folds in the Triassic and Jurassic rocks have produced additional strain in Newark basin sedimentary rocks.

100 m north of the northern edge of the basin are found in the fanglomerate (Stop 11).

4. Boulders of local dike rocks from the Rosetown extension of the Cortlandt Complex have been found at three localities in the fanglomerate.

These observations suggest that the rocks now exposed at the surface in the footwall and hanging wall blocks could not have been separated greatly following Sinemurian deposition.

Intrusive activity in the northern Newark basin and origin of the lava flows at Ladentown

The Palisades sill (Walker, 1969) is intruded into Upper Triassic rocks of the Newark basin and has been dated by ^{40}Ar/^{39}Ar technique at 193 ± 9 m.y. (Dallmeyer, 1975). The Palisades sill crosscuts rocks as young as the basal part of the Lockatong Formation of late Carnian Age at the Hudson River but cuts up section possibly into rocks of Norian Age near Mount Ivy. Basaltic lava flows constituting the Watchung Basalt are Hettangian in age (Early Jurassic) based on palynomorphs (Cornet, 1977) and fish zonations (Olsen, this publication). Whole-rock K-Ar ages for the Watchung Basalt lava flows range from 193-136 m.y. (Houlik and Laird, 1977), but the ages younger then 193 m.y. are treatable only as minimum ages.

Pillow basalts and pahoehoe-type lava are exposed at Union Hill (Suffern) and at Ladentown at the north end of the Newark basin. Kummel (1898, p. 41) suggested that the Ladentown flows might be the result of a fissure eruption. Aeromagnetic, outcrop, and drill data suggest that the western end of the Palisades sill might extend westward as a feeder to the Ladentown lava flows. A gravity and ground magnetic survey done by students at Lehigh University working with Ken Kadoma in the critical area of possible connection, suggests that two near-vertical feeder dikes extend westward from the Palisades termination at the Palisades Parkway. Either one or both of these join with a possible feeder located at Camp Hill (see discussion Stops 6 and 7).

Mapping of the Ladentown exposures reveals abundant evidence for multiple flows, pahoehoe lava, and composite lava flows. Three main flow units separated by vesicular zones, are recognized. The basaltic rocks extend southwestward to the Ramapo fault where the lavas have been cored in two holes that document a thickness greater than 450 feet.

The Ladentown exposures are especially significant because of the apparent crosscutting relationship of the flows to structure in the underlying Triassic

fanglomerate. Ladentown flows fill a structural basin produced by intersection of two fold systems, a longitudinal northeast-trending syncline parallel to the Ramapo fault and a transverse northwest-trending syncline (Fig. 8).

The base of the lava flows appears to decrease in elevation from northeast to southwest and to cut across, flowing in an apparent channel, northeast-dipping strata on the western limb of the longitudinal syncline. Pahoehoe tongues and lobate bulges suggest flow directions to the southwest down the apparent channel.

One possible interpretation of the data is that the Ladentown lava flows are a surface representation of the Palisades magma that was erupted from a fissure feeder onto already folded strata. Flowage of lava in a southwesterly incised drainage pattern resulted in ponding against the border fault in the vicinity of the Sky Meadow drill site. Pre-flow rotation of the Triassic strata could have been produced by drag on the border fault, causing the longitudinal northeast-trending syncline.

Subsequent northwest and additional northeast folding postdated the flows as the border fault was reactivated as a right-oblique normal fault as documented by core drilling at the Sky Meadow site.

Drill coring at the western edge of the Ladentown flows showed composite flows resting on black organic siltstone. This organic siltstone may have been deposited in sag ponds locally developed near the border faults.

If the above interpretation proves correct, then faulting and folding of Triassic strata preceded eruption of the lava flows at about 193 m.y. or earliest Jurassic time. These are the first observations that suggest that longitudinal folding near the border fault may have developed during sedimentation.

The presence of cobbles of basaltic pillows in association with the coarse boulders of brecciated dolostone seen at Union Hill (Stop 6), just beneath the lava flows suggests that basaltic activity preceded eruption of the flows at Mount Union. Boulder and cobbles of rhyodacite dikes found in alluvial gravels associated with fanglomerate from Ladentown south to the New York Thruway at Suffern can be traced to the Rosetown dike swarm found to the north in the Proterozoic and indicate that a southerly-directed drainage system was present near the border fault prior to eruption of the Mount Union-Ladentown lava flows.

Speculations regarding the folding of pre-Hettangian (lowermost Jurassic) strata adjacent to the border fault

suggest that growth tectonics may be applicable to the Newark basin and that faulting and folding began before 193 m.y. ago or 20 m.y. before initiation of coherent, large-scale ocean-floor spreading estimated to have begun from ages of extensional dikes (May, 1971; Sutter and Smith, 1979). In the Hartford basin rotation of 191 m.y. old lava flows, sills and strata as young as Toarcian-Bajocian (late Early to early Middle Jurassic) preceded intrusion of the Fairhaven dikes at 175 m.y., or late Early Jurassic, which are not rotated (Sutter and Smith, 1979). Uncertainties in age assignments for stratigraphic units and dikes lead to the possible overlap in ages.

Despite extensive hydration of the Ladentown basalt, table 1, the TiO_2, Fe_2O_3, and SiO_2 values are comparable with values for the Palisades chill dolerite and to pigeonite dolerite corresponding to Palisades magma types 1 and 2 of Walker (1969). Total iron oxide for the Ladentown is distinctly lower than third Watchung basalts (Faust, 1975, table 2). The TiO_2 content and major-element chemistry of the basal flows of the Ladentown resemble magma types of Pennsylvania at Rossville and York Haven and the "First" and "Second Watchung" flow units (Black and Piburn, 1972; Smith, Rose and Lanning, 1975). Chemical analyses of Ladentown basalt (Geiger, Puffer, and Lechler, 1980) reportedly resemble closely the second Palisade magma type. They suggest, as did Savage (1968, p. 90), that the Ladentown flows are Palisades magma that erupted on the Early Jurassic land surface.

The available geophysical, geochemical and geologic data suggest that the Ladentown lavas represent a fissure-flow eruption fed by the Palisades sill or an off-shot of the same magma chamber that fed the Palisades. The indications are that the lava extruded across previously folded and dissected Triassic strata.

If we can assume that the lava is 193 m.y. old (coeval with the Palisades sill), then we are looking approximately at the same level of erosion with respect to Palisades sill as existed in earliest Jurassic time.

If the sediments at the base of the lava flows are earliest Jurassic in age, then the total stratigraphic thickness of the sedimentary rocks at the north end of the Newark basin (northeast of Ladentown to Stony

Table 1   Chemical analyses of lava flows at Ladentown from base of lava flows, compared with Palisades magma and "Third Watchung" basalt.

| | Palisades sill (Avg. chill dolerite) Walker 1969 | Pigeonite dolerite | Ladentown lava flows from Haverstraw Road core | | | | "Third Watchung" basalt (Avg. 36 samples Faust 1975 Table 2) |
			Center HR78*	Top of flow HR74	Pillow basalt HR31**	HR23	
SiO_2	52.0	50.18	49.2	46.3	49.9	51	49.4
TiO_2	1.2	1.57	1.1	1.3	1.2	1.1	1.3
Al_2O_3	14.5	14.63	14.2	16.3	14.7	13.3	13.58
Fe_2O_3	1.35	2.58	3.8	4.6	4.5	4.9	5.08
FeO	8.9	7.77	6.2	4.1	5.6	5.3	9.54
MnO	.15	.14	.23	.21	0.24	.22	.24
MgO	7.6	8.04	7.7	6.7	6.8	7.2	5.65
CaO	10.3	10.29	10.6	9.6	10.1	9.8	9.15
Na_2O	2.0	2.05	2.1	2.8	2.9	2.5	2.96
K_2O	.85	.60	.18	.37	.18	.39	.51
P_2O_5	.15	.25	.14	.16	.15	.15	.17
H_2O	1.05	1.66	4.0	.7	3.8	3.1	2.59
CO_2		nd	.03	2.2	1.1	.38	

*   Sample taken for $^{40}AR/^{39}Ar$ dating by John Sutter

** Sample taken for $^{40}Ar/^{39}AR$ dating by John Sutter at 26 ft.

Point) is probably only 1,000-2,000 m thick and markedly thinner than equivalent age sedimentary rocks in the center of the basin. Olsen (this publication) estimates that approximately 5,000 m of Upper Triassic sedimentary rocks underlie the central part of the Newark basin and that this section thins to about 2,500 m at the eastern edge of the basin at the Hudson River near Jersey City.
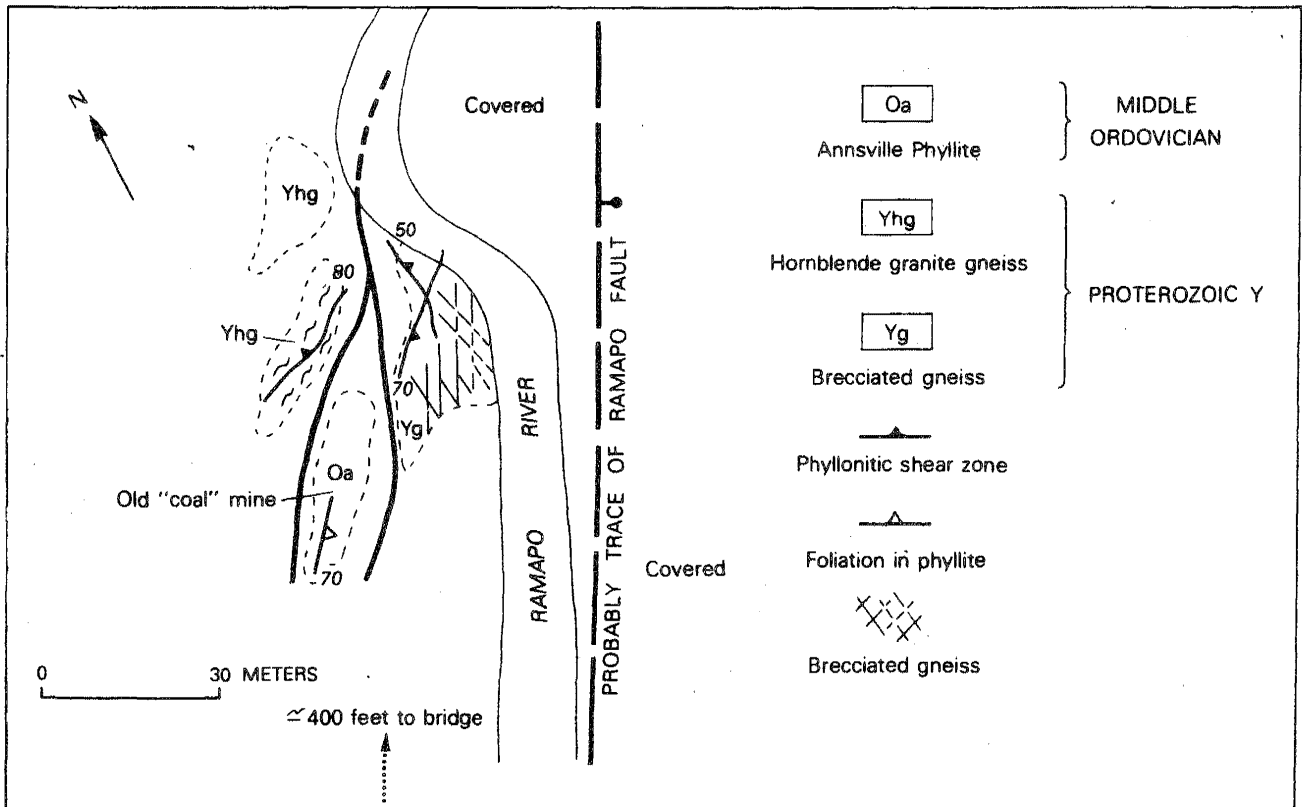
If the Ladentown flows do correlate with the Palisades sill and with the "First Watchung" lava flow as shown on figure 1 then no rock younger than earliest Jurassic occurs in the Newark basin north of the Watchung syncline.

ROAD LOG

Field log begins from intersection of Route 78 and Garden State Parkway headed north from Newark on the Garden State Parkway.

Mileage

3.5   Turn onto 280 W. at E. Orange exit 145

7.5   Excellent crops of "First Watchung" basalt (Orange Mountain basalt in Olsen this guidebook) Minor faults strike N. 20° E. and dip 80° SE. and have broad shear zones with gouge and subhorizontal slickensides.

9.3   Crops of platy jointed basalts of Second Mountain (Preakness Mountain basalt of Olsen, this guidebook)

10.3   View in distance of Hudson Highlands and Ramapo fault escarpment.

16.   Follow 287 to Boonton; watch for right turn.(See Fig. 5 for start of route).

23   Excellent crops of the conglomerate at Montville of Carlston (1946) here contain cobbles of hornblende granite gneiss, epidote veined cataclastic gneiss, "Franklin Marble", and abundant clasts of basalt. These deposits are the youngest rocks in the Newark basin.

23.8   End 287; take Route 202 to left.

[1] Of New York State usage

Fig. 9.   Sketch of field relationship seen at Stop 4 where a sliver of "Annsville Phyllite" is enclosed between mylonitic shear zones. Brittle fractures, microbreccia and cataclasite at the east edge of the exposure illustrates Mesozoic fault fabrics.

25   Turn left on Waughaw Road in Towaco.

25.8   Turn left on Old Lane and crops of gneiss boulder conglomerate.

26.8   Stop at entrance to Mulbrook Lane.

Stop 1. Mulbrook Lane. Stop at end of circle - **Sliver of Cambrian quarzite phyllonite and Ramapo fault breccia**

At east side of circle is brown, very shattered, dioritic gneiss(?). To west up slopes by house are crops of vitreous quartzite of probable Cambrian age. Farther west, across small swale, are excellent crops of pale-green, phyllonite gneiss typical of the more ductile deformation zones in the Hudson Highlands.

Sericite, epidote, and needles of actinolite are found in the phyllonite which exhibits strong right-lateral strain slip folds. Ductile deformation is characteristic of these zones along the western edge of the Mesozoic basin.

This quartzite forms one of a series of similar slivers of Cambrian and Ordovician cover rocks that are found west of the Ramapo fault from Boonton north to Tomkins Cove and are interpreted as fault slivers within the ductile shear zones of pre-Mesozoic age. The phyllonite zone forms a continuous belt along the Ramapo to Riverdale where the shear zone may bifurcate with part of the zone extending northward into the Proterozoic rocks along the Lake Inez shear zone.

The cataclastic rocks east of the circle are more typical of cataclastic rocks associated with Mesozoic faulting on the Ramapo.

Return to bus.

27.8   Return to intersection Old and Waughaw Road; turn left.

28.2   Turn right on Indian Lane - low crops of what may be the 4th Watchung lava flow; excellent crops in gas pipeline.

28.6   Left on Jacksonville Road; follow road to right.

30   Turn left at intersection with Sunset Road.

31   Crops of fanglomerate. Optional Stop 1b.

1b. Optional stop. Roadcuts at entrance to golf course at Jacksonville.

Grey to greenish-grey coarse conglomerate (Jc) that contains fragments of "Franklin Marble", detrital graphite, coarse cobbles fragments of hornblende granite gneiss and epidote-veined phyllonite from the older phyllonite west of the Ramapo fault. To the south, a lava flow younger than the "Third Watchung" lava flow overlies fanglomerate. A waterwell drilled in 1979 penetrated 50 feet of basalt and bottomed at 130 feet in grey and red shale conglomerate near this site.

These sedimentary rocks and the lava flows are the youngest rocks known in the Newark basin, based on the palynology of Cornet (1977) who identified these rocks as Sinemurian (middle Early Jurassic).

The nonfolded outcrop pattern of these Sinemurian

deposits as compared with the marked northwest-trending folds affecting the Watchung lava flows is notable. This suggests to me that the northwest crossfolds may have formed prior to cessation of fanglomerate deposition.

32   Turn left at stop sign, West End Road.

32.4   Mountain Avenue, turn right then left onto Boulevard Avenue.

33.6   Intersect Route 23, cross over, head west to traffic circle.

34.3   Just after traffic circle pull over to right. Stop 2 - cross over highway with caution to large sandpit. Bus will turn around and meet us on east bound side of Route 23.

Stop 2. Large sandpit southwest of traffic circle at Riverdale. (See Fig. 5,6,7).

Discussion of core drilling at Riverdale site and bedrock exposures of phyllonitic shear zones and epidote veined cross faults.

Excellent pavement exposures of phyllonitic hornblende granite gneiss and quartzite paragneiss can be seen. Isoclinal folds with axial planes of N. 35° E., 72° E. are crossed by crossfaults locally marked by epidote veins cross-faults N. 65° E., 72° SE., N. 30° W., 90°, N. 25° W., 85° NE. show predominant left-lateral and reverse movement.

At the south end of pit, a mylonitic grey, quartzose gneiss is crossed by small crenulations and down-to-east faults. Along the entire border fault, phyllonite where present near the Ramapo is crenulated and micro-faulted with veins of calcite and laumontite. This is typical of Mesozoic mineralization. The phyllonite predates the epidote-rich crossfaults that are of unknown age.

In the sand pits to the south, two continuous core drill holes penetrated the Ramapo fault, see figures 6 and 7. The fault offsets fanglomerate of probable Sinemurian Age of the hanging wall against phyllonitic gneiss of the ductile shear zone.

The actual fault is expressed by 1 cm of soft gouge, consisting of pulverized rock material. Below the fault, green phyllonite, like that seen in the exposures here, is crenulated and displaced on normal faults. Excellent recovery of the fault zone material has permitted thin section examination of the actual fault. The sawtooth contact is preserved showing down-to-the-southeast sense of movement with no evidence for reactivation since this last normal movement. Chlorite-coated surfaces, microbreccia and cataclasite, and "mylonitic" cataclasite with a pronounced fluxion structure are common in the cores. The actual fault is remarkably sharp and well defined in each core. The fault dips 50° SE. assuming a N. 40° E. strike as indicated from outcrop data to the south.

Sections of the actual core will be available for inspection. PLEASE DO NOT REMOVE CORE FROM BOXES.

Route 23 east, enter traffic circle, 270° to left; take Newark Boulevard north toward Riverdale.
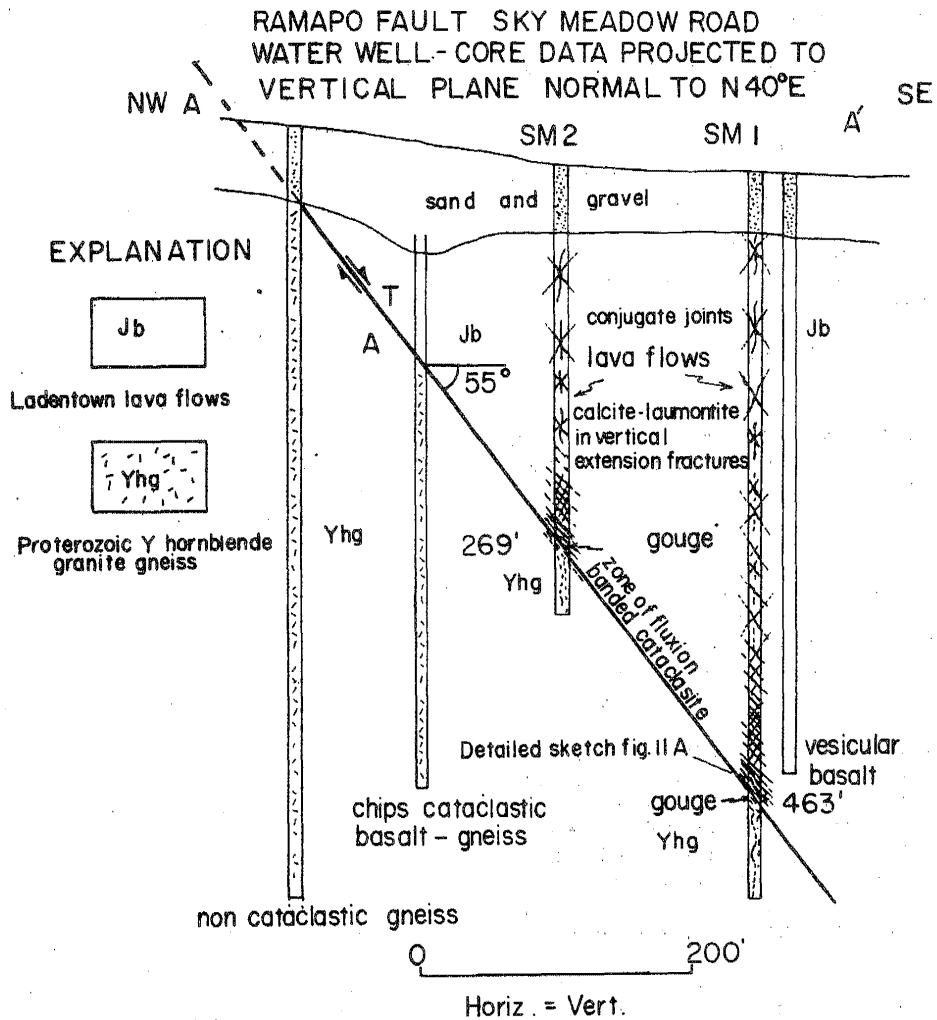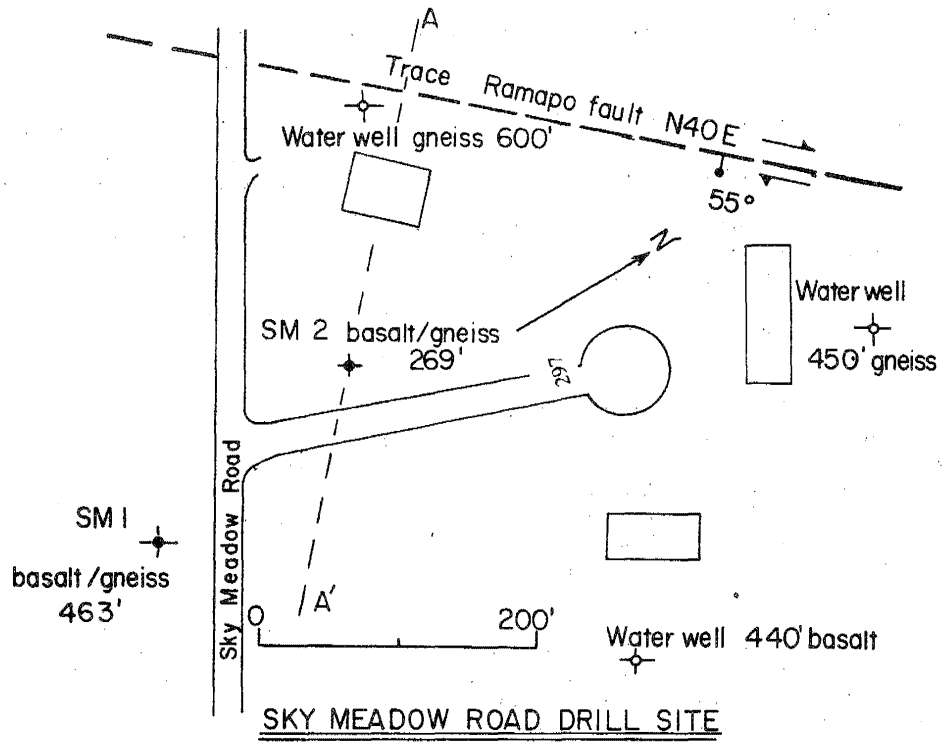
A

Trace Ramapo fault N40E

Water well gneiss 600'

55°

N

SM 2 basalt/gneiss
269'

297

Water well
450' gneiss

Sky Meadow Road

SM I

basalt/gneiss
463'

O   A'

200'

Water well 440' basalt

SKY MEADOW ROAD DRILL SITE

RAMAPO FAULT SKY MEADOW ROAD
WATER WELL - CORE DATA PROJECTED TO
VERTICAL PLANE NORMAL TO N40°E

NW A

SE

A'

SM 2   SM I

sand and   gravel

EXPLANATION

Jb

Ladentown lava flows

Yhg

Proterozoic Y hornblende
granite gneiss

T

A

Jb

55°

Yhg

269'
Yhg

conjugate joints

lava flows

calcite-laumontite
in vertical
extension fractures

gouge

zone of fluxion
banded cataclasite

Jb

Detailed sketch fig. II A

gouge

chips cataclastic
basalt – gneiss

Yhg

vesicular
basalt
463'

non cataclastic gneiss

O   200'

Horiz . = Vert.

Fig. 10.   Generalized diagram showing location of drill holes and
water-well data penetrating Ramapo fault at Sky Meadow
Road site.

35.6   Turn right at intersection for Pompton Lakes.

36.4   Turn left on Riverdale Road to Wanaque.

40.0   Turn right on Belmont Avenue just after WANA-Q Pizza, follow circuitous route to small cottage at north end of sand pit. Walk east from cottage to opening in sand pit.

Stop 3. Lake Inez shear zone exposures in abandoned sandpit.

Pavement exposures of phyllonitic, amphibolite gneiss and pink pegmatite show right-lateral displacement of pegmatite on N. 15° E., 30° SE. dipping shear zones. Chlorite, epidote and sericite mark phyllonite zones. Later cross faults N. 65° W., 60° SW. show left-lateral displacement of shear zones and are marked by veinlets of epidote. This is the northerly extension of the same shear zone seen at Stop 2.

Up the hillside to the east, exposure of gneiss show reactivation of gneissic layering. Within this area, all suitably oriented surfaces, gneissic layering, mylonite zones and more brittle thrust faults all show evidence of reactivation in the Mesozoic movement sense. Widespread reactivation in this area follows the steep northeast-trending structural grain developed in "Grenville" and Taconic tectonism.

Log resumes at Belmont and Riverdale Road, turn right on Riverdale Road.

43.1   Turn right on Skyline Drive - excellent crops in Erskine area show abundant brittle faults as well as more ductile ones. Reactivation has been widespread.

45.8   Near crest of hill at gas pipeline epidote-filled cross fractures with excellent wear grooves suggest Mesozoic reactivation.

48.2   Stop sign; turn left and cross River; follow signs to 202 north.

50.1   Exposures of faulted basalt, turn left on Navajo Road, bend around south shore of Crystal Lake and turn right on Lenape Street.

50.3   Park at bridge west shore. Stop 4.·

Stop 4. (Optional stop) "Coal Mine"

Reports from a desultory mining operation in the late 1800's refer to small coal prospect on the west bank of the Ramapo River ¼ mile north of Crystal Lake.

This exposure is a sliver of coal black graphitic phyllite ("Annsville Phyllite") similar to the exposure along the border fault at Riverdale. Sketch map figure 9 shows the relations. The sliver of black phyllite is found between two outcrops of gneiss. Very mylonitic gneiss is located to the west. Gneiss exposed east of the sliver has a composite fabric with brittle fractures and abundant microbreccia. The relationships seen here are similar to those seen at Stop 1 and those to be seen at Stop 9 on the Thiells fault. The brittle fractures are spatially related to Mesozoic faulting; the more ductile shears are associated with thrust and strike-slip faulting of probable Ordovician age and represent the southwestward extension of the Canopus zone fault

exposed north of the Newark basin. Drill holes for water wells about 400 feet north of this site penetrated granite gneiss in holes 500 feet east of this locality. The "Annsville Phyllite" inclusion does not occur within the Mesozoic border fault but lies west of it as part of the footwall block.

50.5   Return to Route 202, turn left.

58   Turn left under RR tracks; follow Route 202 north to Suffern.

58.6   Stop on[·· ··· ····]Koon Restaurant. (See fig. 8 for location).
Stop 5. Optional Stop. **Cataclasite and fault fabric in cataclastic gneiss at Ramapo fault, Suffern.**

These small exposures of black, chlorite-coated, cataclastic, hornblende-granite gneiss are much more instructive than the exposures north of Suffern commonly visited by field trips. Excellent chlorite-slick surfaces dip in conjugate fashion northwest and southeast and exhibit down-to-the-south right-oblique slip on southeast-dipping surfaces and down-to-the-west and left-oblique movement on southwest-dipping surfaces. The near-vertical attitude of the extension fractures here and in the Sky Meadow drill core suggests that the rocks of the footwall block have not undergone rotation after formation of the cataclastic fabric.

58.9   Right on LaFayette Avenue, continue past circle to entrance to N.Y. telephone building - park in lot.

59.2   Stop 6 - Plaza Stone Quarry - Union Hill

We are permitted entrance with the clear understanding that we will not attempt to enter the quarry proper. Please respect the owners' wishes. Use extreme caution near steep cliffs on west side of exposure.

Stop 6. Union Hill trap quarry and contact of lava flows with fanglomerate.

Superb exposures at the south end of the quarry near the rock crushers show a vertical wall of coarse fanglomerate, enclosing a large boulder of brecciated dolostone in an apparent channel that, in turn, is overlain by an upward-fining cycle ending·in fine red shale with greenish slate chips. Vesicular pillow lava directly overlies this shale.

Clasts in the fanglomerate include epidote-rich hornblende granite gneiss, Silurian Green Pond conglomerate, dolostone clasts, and several cobbles of basalt pillows. I interpret the large boulder as a block of breccia from the border fault, and the clasts of pillow basalt as blocks eroded from the southward-advancing Ladentown lava flows.

In the Ladentown-Suffern area, alluvial deposits such as those seen here contain boulders of felsic dikes uniquely traceable to the Rosetown dike swarm. These data indicate, as do the observations at the next stop, that a southerly-directed Jurassic drainage system was present near the border fault prior to eruption of the flows at Ladentown and Mount Union. Perhaps the debris flow material seen here are earthquake-activated deposits formed immediately prior to extrusion of the Ladentown basalt. The basalts seen here are correlated with basalts of the "First Watchung" on the opposite limb of the Suffern cross anticline.

59.7   Return to traffic circle on LaFayette; turn right on 202.

63.0   Sky Meadow Road - drill site is at base of mountain to left.

63.6   Limekiln Road; turn right; stop at top of hill.

63.8   Stop 7

Stop 7. Basalt at Ladentown and discussion of drill data from the Ramapo fault.

Note exposures and attitude of red quartz-pebble arkose by road and walk north to ridge behind house. Multiple basaltic lava flows with pahoehoe tongues and snouts as well as small pressure ridges may be seen. BE VERY CAREFUL NOT TO DISLODGE BLOCKS THAT WOULD TUMBLE INTO THE BACKYARDS OF THE HOUSES BELOW. Flow direction obtained from similar exposures suggest that the lava flows were flowing southwest toward the border fault and that the base of the lavas flows are at lower elevations to the southwest.

Drill-core data from Sky Meadow Road suggest that vesicular lava and multiple flows of lava more than 450 ft. thick accumulated near the border fault. These speculations would require a local relief in the basin adjacent to the border fault of approximately 450 ft.

Results of the drilling of the border fault will be discussed (see text).
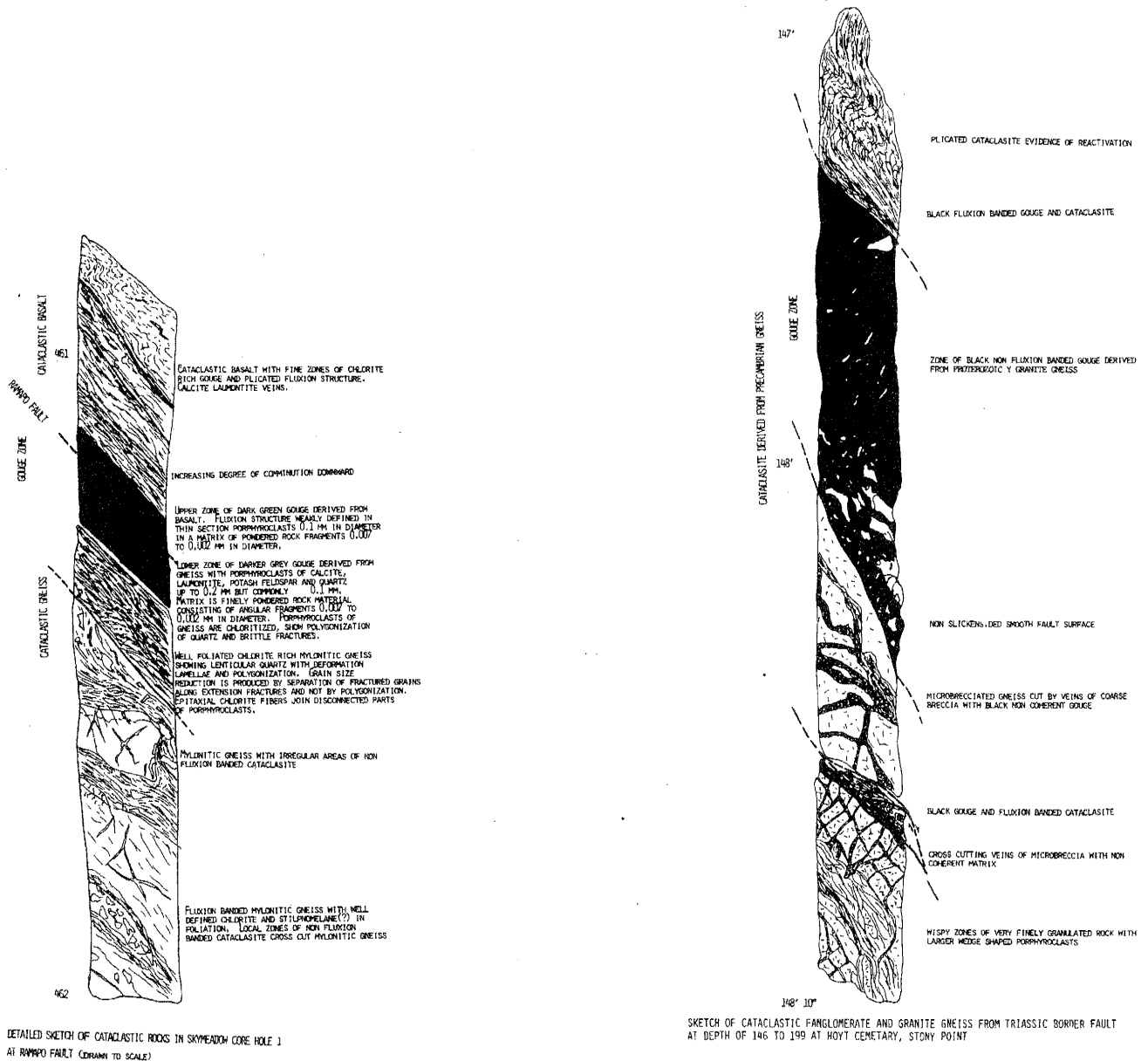
Continue east on Limekiln.

DETAILED SKETCH OF CATACLASTIC ROCKS IN SKYMEADOW CORE HOLE 1
AT RAMAPO FAULT (DRAWN TO SCALE)

SKETCH OF CATACLASTIC FANGLOMERATE AND GRANITE GNEISS FROM TRIASSIC BORDER FAULT
AT DEPTH OF 146 TO 199 AT HOYT CEMETARY, STONY POINT

Fig. 11.   Detailed sketches of cataclastic rocks seen in drill cores across Ramapo fault at Sky Meadow Road and at Hoyt Cemetery, Stony Point drill core 2 in. in diameter. A - Sky Meadow Road; B - Cem. No. 1, Stony Point.

Excellent pavement outcrops of limestone.

64.2   Fanglomerate found immediately below Ladentown lava flows (optional stop) just past intersection.

65.0   Light turn right on Route 306.

66.5   Route 202 continue straight across to Ladentown.

66.7   Bear right then left on Call Hallow Road.

68.0   Turn right on access road leading up to watertank. Stop 8.

Stop 8. (Optional stop). **Excellent exposures of Mesozoic fault features on Cheesecoate Mountain north of Newark basin and view of Newark basin.**

This block of Proterozoic gneiss lies east of the Ramapo fault but west of the Thiells fault. It may represent a horst of basement rock that was structurally high during Triassic sedimentation. The principal argument in favor of this contention is the dominance of northeast-striking faults that appear to pass into the basin but do not disrupt the continuous belt of intrusive and extrusive lava.

Continue north on Call Hallow Road to Willow Grove.

69.7   Turn right on Willow Grove Road, pass under Palisades Parkway. We are traversing a belt of gneiss that possibly forms a horst block between the Ramapo fault and the Thiells fault.

71.0   Turn right on Hammond Road.

71.7   Stop at intersection of Suffern Lane at Thiells. Stop 9.

Stop 9. Thiells fault.

This small but significant exposure (Fig. 12) illustrates well the difference between Mesozoic faults as seen in drill record and the older mylonitic faults of probable Ordovician age. The Thiells fault is an oblique-thrust fault that juxtaposes the Manhattan Prong rocks against those of the Reading Prong. Abundant ultramylonite, pseudotachylite, and mylonite with metamorphic mineralization affects Proterozoic Y and Paleozoic rocks everywhere along the fault. Figure 12 shows the structural relationship exposed in the small quarry behind the houses.

K-Ar data on sericite that replaces mylonitic quartzite yields an age of 379±13 m.y. (386 m.y. using newer constants). K-Ar data on pseudotachylite from a locality to the north gave an age of 259 ±9 m.y. (264 m.y.). The mylonitization and sericitization associated with the fault are totally unlike that found on any proven Mesozoic fault.

Fracturing in the quartzite at the east side of the exposure may be related to Mesozoic faulting. The similarity of this exposure to that seen at Stop 1 is striking.

Return north on Hammond Road to stop sign.

72.4   At Willow Grove Road, turn right.

72.6   Turn left on Goethius Bridge Road.

73.3   Continue north to Route 210 intersection and Stop 10.

Stop 10. Triassic quarzite-rich fanglomerate and cataclastic

Annsville at Cedar Pond Brook, Stony Point. (See fig. 14 for location).

Exposures of black cataclastic "Annsville Phyllite" may be seen at the banks of the small pond west of the dam. Thin-section examination of the east-dipping fabric reveals up-from-the-southeast microdisplacements and abundant clinozoisite and sericite replacement veinlets. This fabric is associated with the Thiells fault that crops out to the west.

A light-colored conglomerate of uncertain origin overlies phyllite and contains fragments of brecciated "Wappinger Limestone" and "Annsville Phyllite". This conglomerate may be a basal triassic conglomerate deposited unconformably on the cataclastic "Annsville Phyllite". Light-grey carbonate-rich conglomerates similar to this are found along the unconformity at Tomkins Cove to the north.

Large crops of coarse fanglomerate are seen at the dam to the northeast. Quartzite clasts dominate. Cambrian Poughquag Quartzite crops out 1,000 ft to the west where it forms an unconformable cover on the gneiss of the Hudson Highlands west of the Thiells fault. This suggests very local source area for the fanglomerate and further suggests that little post-depositional separation has occurred in this area.

Drill data from cores and trenches 800 ft to the north are shown in figures 13 and 11. A normal fault dipping 70° SE. was intercepted in two vertical drill holes. Cataclasite and gouge typical of other Mesozoic faults marked the fault zone. Unexpectedly, gneiss forms the footwall in Cem. 1. A possible interpretation of the data is shown in figure 13. It is notable that none of the distinctive ultramylonitic rocks seen at the Thiells fault (Stop 9) were found at the border fault. This illustrates the difference between Mesozoic brittle fault products and ductile fabrics of Ordovician faults.

Turn right on Route 210.

74.3   Route 9 W turn left.

74.9   Turn right at sign marking entrance to Stony Point Battlefield.

76.0   Continue to entrance to park at RR tracks and park. Stop 11.

Stop 11. Fanglomerate at Stony Point at northern end of Newark Basin.

Limestone fanglomerate unconformably overlies Inwood Marble and "Annsville Phyllite" along the east-west Triassic outcrop belt at Tomkins Cove. Exposures in the railroad cut along the slopes contain inclusions of dolostone traceable to the immediately adjacent dolostone in the Tomkins Cove quarry. Small chips of distinctive biotite-rich hornfelsed Manhattan Schist typical of the contact facies bordering the Cortlandt Complex have been found in the fanglomerate at this locality. Very local sediment sources are suggested by these data.

END SATURDAY TRIP

ROADLOG FOR SUNDAY TRIP

Assembly point is entrance to Stony Point Battlefield; same location as end of Saturday trip. (See fig. 14 for location).

For early arrivers, a brief tour of the exposures of the Cortlandt Complex in the park will be possible.
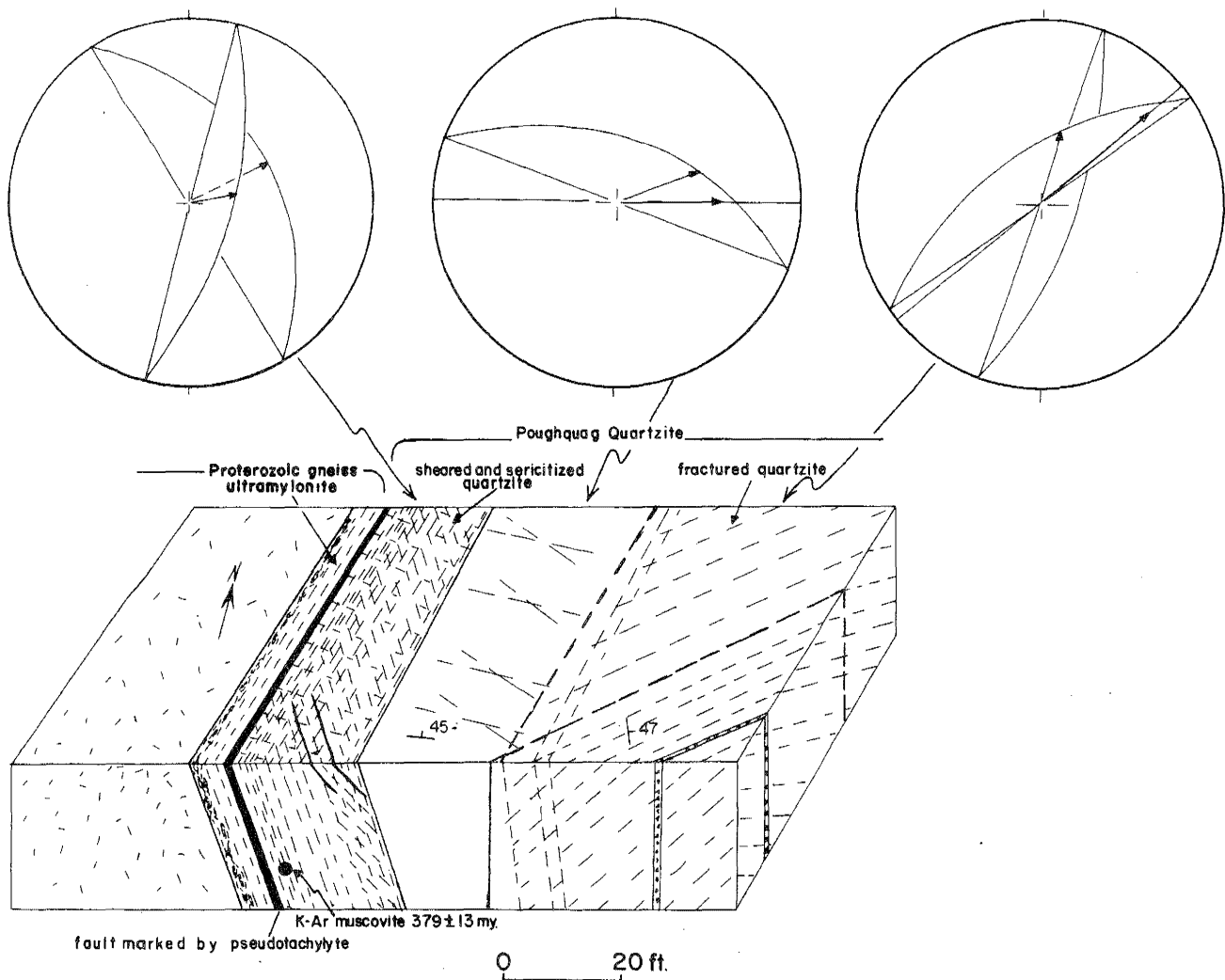
Mileage

Leave Stony Point Battlefield

0.5   Turn right on 9W

1.0   Turn right at entrance to Hudson River Aggregates Tomkins Cove quarry - drive to entrance and wait for guard to open gates.

Hard hats are required - no climbing of talus slopes and *please* stay away from overhanging walls.

Stop 12 Tomkins Cove quarry in "Wappinger Limestone" (Inwood Marble) and fault exposures north of the Newark basin.

This large quarry in "Wappinger Limestone" (Fig. 14) forms the axial portion of a westward overturned anticline bordered by "Annsville Phyllite" on the west and Manhattan Schist unit A on the east.

Well-layered beige-to-tan weathering quartzose dolostone with phyllite partings forms the central part of the quarry and is bordered on the west by southeast-dipping overturned but highly folded light gray nonquartzose dolostone and black phyllite.

Poughquag Quartzite

Proterozoic gneiss ultramylonite

sheared and sericitized quartzite

fractured quartzite

45

47

K-Ar muscovite 379±13 m.y.

fault marked by pseudotachylyte

0   20 ft.

Fault zone Thiells, N.Y. PK 764

Fig. 12. Block diagram of fault at Thiells, N.Y., showing intensely developed zone of ultramylonite, and pseudotachylite at contact of Cambrian Poughquag Quartzite and Proterozoic Y hornblende granite gneiss. Sericitization is pronounced in ultramylonite and in Poughquag immediately east of fault. Nonaligned muscovite replacing quartz in the fault zone yields a K-Ar mineral age of 379±13 m.y. Lower hemisphere equal-area projections of dominant shears, in three areas, and some lineations are shown.

The muscovite age yields a minimum age of the faulting at this locality. Because the same fault offsets rocks as young as Middle Ordovician to the north, the fault is Late Ordovician to Devonian in age and is regarded as a Taconic fault.

Planetable mapping of the quarry at 1'' = 200 with structural geology students at City College has shown that straight forward correlations of units across the quarry is not possible because of eight major fault zones that disrupt the structural continuity. These faults are expressed by red or green zones of clay gouge and phyllonite. Several of these features can be seen on the south face of the quarry exposed in all three levels.

Structural analyses of the fabric associated with these faults indicate that most are southeast-dipping reverse faults with left-lateral or right-lateral components of movement. Minor folds within shear zones plunge steeply down the dip of fault surfaces, commonly normal to slickensides. Faults are located on the limbs of isoclinal overturned folds exhibiting excellent metamorphic fabric and ductile fold styles.

Despite the young looking nature of these faults they appear to be compressional features formed during Taconic dynamothermal metamorphism. Reactivation may have produced the clay gouge and slickensides locally.

Within the quarry, at the extreme west in corner of level 2 and near the southeastern corner of level 3, N.S. steep north-trending faults offset the older clay gouge zones and produce drag folding of older slickensided surfaces.

The western fault is coated with fibrous palygorskite that forms an excellent slickenside lineation. K-Ar dating of this mineral by H. Kruger yielded an age of 183 ± 31 m.y. These data suggest that the prominent clay gouge seams seen in the quarry are older than 183 ± 31 m.y. The palygorskite-coated fault probably is Mesozoic. The fact that the red claygouge thrust fault zones are not recognized in the Triassic rocks immediately overlying the dolostone to the south also suggests that the main faults seen here are pre-Mesozoic in age.

From these observations, I conclude that the faults seen here are (1) Ordovician thrust faults possibly reactivated in Triassic time to produce gouge, and (2) steep Mesozoic normal and strike-slip faults.

If it were not for the K-Ar age from the palygorskite one might suggest that the clay-gouge zones represent zones of current thrust reactivation in the present compressive stress field related to present-day seismicity. This stop illustrates well some of the complexities in correlation of seismic events with fault surfaces. Any one or all of the faults seen in this area (Stop 9, 10, 12) and shown on figure 14 might satisfy the available fault plan solutions (see fig. 2) available for this area.

Turn right on Route 9W. Log resumes.

Continue north past outcrops of mylonite biotite gneiss and amphibolite of Ordovician fault zones.

2.8   At swale, trace of Mott Farm Road fault and cataclastite typical of Mesozoic faults trending N. 70°-80° E. View of Indian Point reactors to east.

Long up-grade traverses hornblende granite gneiss and

abundant semiductile faults with associated lamprophyre dikes on Dunderberg Mountain.

5.8   In swale, trace of Timp Pass fault zone of a composite fault zone with evidence of Proterozoic Y, Paleozoic and possible Mesozoic fault activity. This is a major fault that is traceable northeastward through the Hudson Highlands as a metamorphic semiductile fault zone. Very distinctive blastomylonite and a zone of intense folding accompanied by injection of pegmatite mark this fault in many localities. Excellent exposures here of tectonic breccia with inclusions of calcsilicate rocks in a ductile matrix of marble.

6.5   Take Bear Mountain Bridge and turn right south on Route 6 and 202. Note excellent exposures of rusty paragneiss and calc-silicate rock with typical Mesozoic fault fabrics. Exposures of quartz plagioclase gneiss, amphibolite and white alaskite gneiss. Numerous semiductile faults are present in this area.

8.8   Pull off at overlook - view of Hudson River, Dunderberg Mountain and discussion of regional fault patterns.

Stop 13

In the nearly continuous exposures along Route 206 from the Bear Mountain Bridge south to Camp Smith numerous faults have been mapped. These faults are predominantly the semiductile type with excellent phyllonite zones and abundant evidence for right-lateral oblique thrust faulting. Correlation of tectonic features across the Hudson to Dunderberg Mountain is excellent and northeast-trending Mesozoic faults are largely absent. Mesozoic faults are predominantly north- and northwest-trending suggesting that the left-handed bend in the Hudson River here is controlled by brittle fractures of Mesozic age.

These outcrops of biotite granite gneiss are not clearly either "Storm King Granite" or "Canada Hill Granite". However, intrusive relationship in amphibolite can be seen in the roadcuts. A comparison of this rock with the "Reservoir Granite" seen at the next stop is in order.

9.7   Excellent exposures of amphibolite, alaskite, and hornblende granite gneiss ("Storm King Granite") may be seen at sharp bend in road.

11.2   Entrance to Camp Smith and trace of a major semiductile fault--Wallace Pond fault.

At traffic circle bear right on Route 6 and 202; follow 202 and 6 right after bridge. Annsville Creek.

12.3   Pull off at overlook. Stop 14.

Stop 14. "Reservoir Granite" and mylonite zones

The "Reservoir Granite" (Berkey and Rice, 1919) is a widespread granitic rock type east of the Canopus fault zone. Doug Mose has dated a collection of rocks from this locality and from northeast of here and obtained an Rb/Sr isochron of approximately 1250 m.y. for both collections (Helenek and Mose, 1976). The granite has intrusive contacts with amphibolite with which it is commonly associated and may represent either remobilized felsic volcanic rocks (interlayered with amphibolite) or truly intrusive granite.
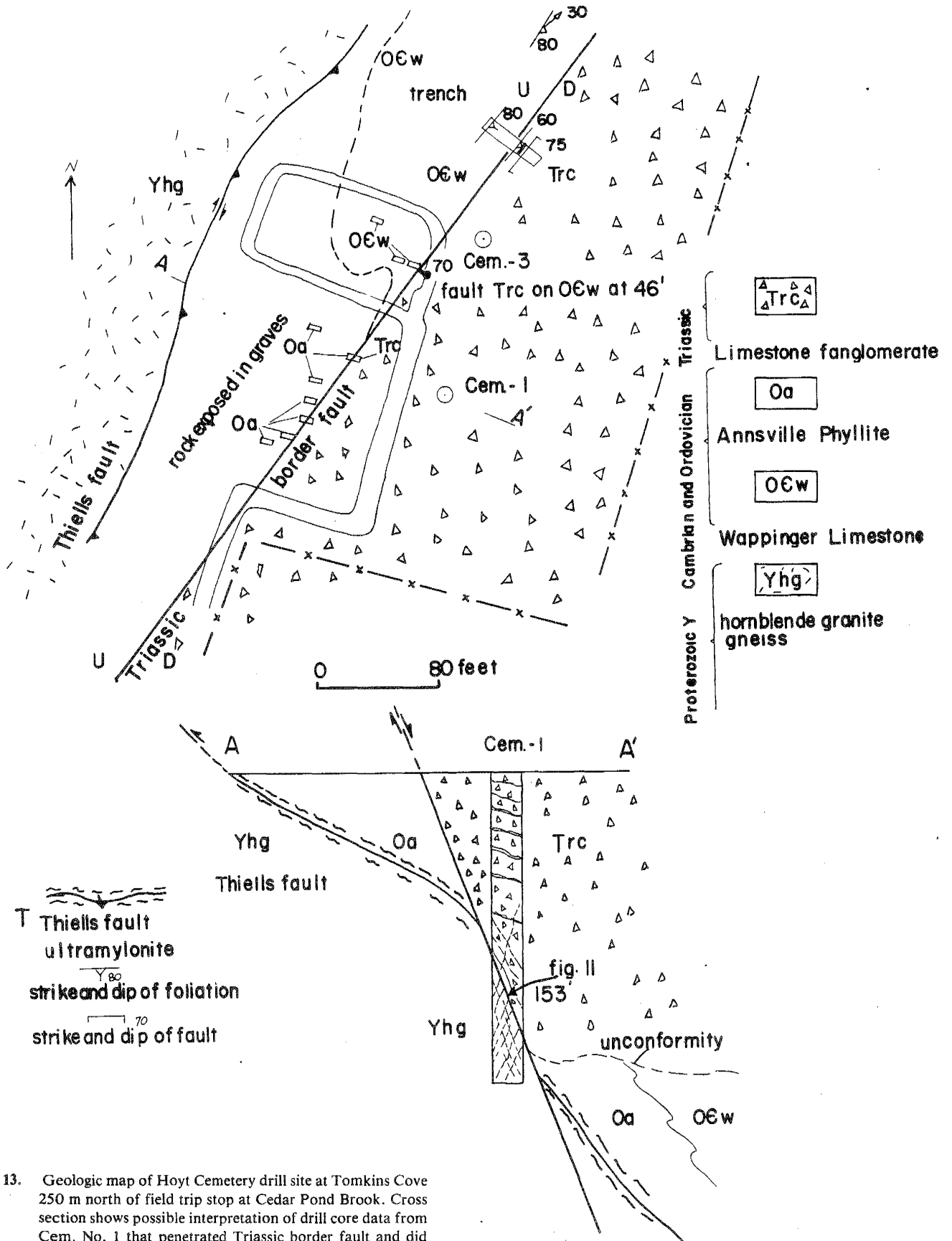
Fig. 13. Geologic map of Hoyt Cemetery drill site at Tomkins Cove 250 m north of field trip stop at Cedar Pond Brook. Cross section shows possible interpretation of drill core data from Cem. No. 1 that penetrated Triassic border fault and did not cross ultramylonite or mylonite such as that seen at Stop 9.

Excellent mylonite zones cut this garnet-bearing granite. Biotite-rich blastomylonite zones contain syntectonic garnet and intrafolial folds indicating right lateral movement. "A" lineations are subhorizontal. The granite gneiss has biotite and muscovite growing in ductile shear zones and garnet is retrogressively altered to biotite. This tectonic fabric probably represents Ordovician retrogression. The regional grade in Middle Ordovician rocks at this locality is between biotite and garnet zone.

12.5   Exit for Route 35 turn left and return north on Route 6 and 202, continue north to traffic circle and follow Route 9 north.

16.0   Low road cuts of phyllite.

Stop 15. Optional **Annsville fault - tectonic breccia**

Exposures of marble with rounded inclusions of gneiss were cited by Bucher (1957) and by Ratcliffe (1971) as evidence for Middle Ordovician erosion beneath the "Annsville Phyllite". I have changed my opinion of this strange rock and interpret this polymict breccia as a tectonic-mylonitic breccia resulting from large-scale extension and flowage in Proterzoic shear zones. Dismembered calc-silicate rocks form the inclusion within the strongly flow-banded marble. Breccias like this are present throughout the Hudson Highlands and are not restricted to zones of Paleozoic faulting.

A fault between "Annsville Phyllite" and this marble is exposed on the north side of these cuts, where the flow-banded marble is dragged in right-lateral sense into the N. 40° E.-trending Annsville fault. Right-lateral minor folds in fluxion banded rocks and minor thrust faults suggest right-lateral, oblique thrust faulting. Exposed contacts in the sand pits to the north, reveal ribbon-quartz mylonite and diapthoritic phyllonite. Syntectonic muscovite, tremopite, actinolite, epidote, and phlogopite are formed in sheared rocks of appropriate composition.

I interpret the Annsville fault as a post-Middle Ordovician, probably Late Ordovician fault, perhaps equitable with the Thiells fault.

Numerous earthquakes have been recorded in the Annsville area, most recently in January 1980 (Fig. 1). Despite the repeated activity, faults of probably Mesozoic age are largely absent. Faults seen at the surface are all characterized by mylonitic-ductile deformation. The northeast-striking, southeast-dipping phyllonitic shear zones satisfy the available fault-plane solutions.

Turn right for Annsville and turn left after light onto Spout Brook Road and follow this north to intersection with Gallows Hill Road. Turn left. Continue north to Continental Village, take right fork.

19.0   Park at aqueduct crossing

Stop 16. Canopus pluton and western Canopus fault: a probable Proterozoic Y fault zone. (See figs. 16a,b,c and 17

Road cuts of quartz monzonite and granodiorite of the Canopus pluton. Large rectangular microcline-perthite phenocrysts, showing Rapikivi-like mantles. produce a

striking igneous lamination trending north to northwest. Ductile shear zones related to the Canopus fault show right-lateral drag of the older fabric. Locally small pegmatite dikes crosscut augen, gneiss and sheared igneous rocks.

The Canopus pluton has been interpreted as a Proterozoic Y syntectonic pluton on the basis of Rb/Sr and K-Ar dating by Dick Armstrong (Ratcliffe and others, 1972). The pluton is deformed in a right-lateral shear couple.

19.5   **Stop 17 Mylonite gneiss in western Canopus fault**

Strongly mylonitic gneiss at the eastern border of the Canopus pluton are exposed in the road cuts. Biotite-rich blastomylonite and more felsic, mylonitic, quartz-feldspar layers produce a strikingly well-layered rock. Reclined, right-lateral, isoclinal folds plunge steeply southwest in the N. 20° E., 80° SE. dipping shear fabric. A strong lineation is produced by the intersection of compositional banding and mylonitic foliation. The tectonic fabric seen here is restricted to local shear zones of Proterozoic Y age.

Continue north.

21.2   Turn right, follow sharp bend in paved road.

21.3   Turn left on dirt road.

22.3   Turn right on paved road.

22.5   Park on shoulder opposite H. Abrams house.

Stop 18 Eastern Canopus fault and overprint by probable Paleozoic fault fabric of the Dicktown fault. (See fig. 17)

Walk east to base of small cliffs.

This is a complex fault zone, consisting of pink and black biotite-rich augen, gneiss, biotite-rich blastomylonite and intrusive pegmatite. Excellent right-lateral folds, adjacent to ductile shear zones, plunge S. 45° E.

A dark-gray mafic dike crosscuts sheared gneiss and blastomylonite. Metamorphosed dikes like this one are common throughout the Hudson Highlands and are possibly of Proterozoic Z age. Chemically these dikes are distinct from lamprophyres and from Triassic diabases and are currently being studied. No definitive age data are currently available. However, K-Ar whole-rock dates range from 900 m.y. to 240 m.y. in six samples. The fact that they are metamorphosed, locally foliated, and confined to rocks of Proterozoic age suggests that they are old dikes. A series of small mafic stocks, dikes and small plutons are recognized in the Highlands in the vicinity of the Canopus pluton. Those igneous rocks are mafic to ultramafic and always are strongly metamorphosed. These mafic rocks and plutons represent a very obscure period of igneous activity in the Hudson Highlands but appear to be post- to very late syntectonic in the Proterozoic Y deformation. Locally they are extremely abundant.

A traverse up the hill from this point is instructive and shows increasing progressive overprinting of the Canopus fault fabric by the Annsville-Dicktown fault. In

the Dicktown fault zone biotite and garnet are retrograded to chlorite and chlorite rich phyllonite is common. The contrast in the metamorphic grade of a retrogressive mineral assemblages within mylonite rocks may be useful in distinguishing Proterozoic Y faults from Ordovician ones in this area. To the east the Paleozoic grade increases to sillimanite zone and mineral assemblages within mylonites of both Proterozoic Y and Paleozoic age are not distinguishable. Outcrops at this stop, however, are well within the area of relict Proterozoic Y Ar^{40}/Ar^{39} biotite ages obtained by Dallmeyer and Sutter (1976). These data suggest that the Proterozoic rocks of this area never were heated above the biotite blocking temperature of approximately 350 °C since the late Proterozoic. These data are consistent with the assignment of the biotite-rich blastomylonites seen here and at Stops 15 and 16 to Proterozoic Y fault zones. Chlorite-rich phyllonite associated with the Dicktown fault, however, is probably Ordovician.

Throughout the Canopus zone east to the California Hill fault (Fig. 1), no faults having Mesozoic fault characteristics have been recognized, despite detailed mapping. However, as at Annsville, earthquakes are recorded from this zone. The event near the California Hill fault (Fig. 1) is associated with a zone of very ductile, probably Proterozoic faulting.

Faults commonly dip 80° SE. or NW. but locally may dip 60° SE. These tectonic features (Figs. 1 and 4) probably extend through the continental crust and must be present as significant inhomogeneous (weak) zones at depths of 1-10km where earthquakes are occuring. I interpret this highly faulted zone as the ancestral grain that localized Mesozoic faulting in the area to the south traversed on the first day of this field trip. (See fig. 16c)

Turn around and return north on Dennytown Road.

23.5   Bear left on Dennytown Road at Y intersection.

27.5   Intersection Route 301 at Fahnestock Corners. Turn right. Exposures of "Canada Hill Granite" and rusty biotite-sillimanite paragneiss typical of the western block of the Hudson Highlands.

29.5   Canopus Lake - crossing Dennytown fault that marks the beginning of Canopus fault zone, crops of rusty paragneiss, amphibolite marble, calc-silicate rock, and magnetite-bearing quartzite.

30.5   Entrance to Canopus Lake beach area, park at swimming area north end of lake.

Stop 19. Dennytown fault, Poughquag Quartzite inlier (See figure 1 for location)

This exposure marks the southwestern limit of a series of faulted slivers of basement gneiss and Poughquag Quartzite that extend southwest from the front of the Hudson Highlands along the Dennytown fault. These inliers are surrounded by phyllonite zones marked by chlorite-sericite-epidote mineralization and ductile fold styles. Fold axes, within phyllonite plunge southeast in 80° to 60° SE. dipping surfaces. Excellent right lateral offsets and folds are seen in thin section and outcrop. A northeast plunging "a" lineation defines the probable slip direction.

I interpret this fault as an Ordovician, right-lateral, oblique thrust fault parallel to the Proterozoic Y fabric in the gneiss. The northward extension of these fault zones is uncertain but they probably extend out into the Paleozoic cover rocks north of the Hudson Highlands.

Participants from Saturday's trip may be struck by the similarity of these exposures to the quartzite-phyllonite zone seen on Stop 1 near Boonton, N.J. This similarity should drive home the point that phyllonitic shear zones of probable Paleozoic age are regionally important features within the Ramapo seismic zone. Earthquake activity here seems to be more associated with semiductile features such as the Dennytown fault than with brittle-type Mesozoic faults.

END OF TRIP

The Taconic State Parkway intersects Route 301 0.3 miles east of this stop. I-84 intersection with the Taconic Parkway is approximately 5 miles north of that point.

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Fig. 14.   Generalized geologic map of the Tomkins Cove area showing the northward extension of the Ramapo fault (as the Mott Farm Road fault) and the Thiells fault. Semiductile shear zones of the Ramapo-Canopus zone are truncated by intrusive rock of the Rosetown pluton and lamprophyric dikes. Circled stations refer to localities for K-Ar and Rb/Sr studies by Armstrong, Dallmeyer, Mose and this report (Ratcliffe and others, in press). Yhg -hornblende granite gneiss; Ya - amphibolite; Yl-leucogneiss and quartzose paragneiss; Ygg- "Reservoir"-type granite gneiss; Ybq - biotitic paragneiss; Ycs - calcsilicate gneiss. (figure reproduced from Ratcliffe and other, in press).

ROSETOWN PLUTON

Biotite-hornblende monzo-
diorite, monzonite, granodi-
orite and adamellite containing
cognate xenoliths of biotite
and hornblende diorite with
which it is gradational.

Biotite-hornblende and pyroxene
diorite with strong igneous
flow structure in central zone,
contains cognate xenoliths
of hornblende pyroxenite.
Gradational through horn-
blende-rich gabbro to horn-
blende pyroxenite.

Poikilitic hornblende (kaersu-
tite) pyroxenite.

Hornblendite (kaersutite rock)
with flow hornblende.

WESTERN FUNNEL OF BALK

Pluton 4: Hornblende pyrox-
enite, peridotite, cortland-
tite with cumulate layering.

Pluton 3: Clinopyroxenite,
hornblende pyroxenite.

Pluton 2: Green hornblende
gabbro, diorite, biotite quartz
diorite, includes biotite
diorite at Stony Point.

Pluton 1: Brown hornblende
(kaersutite) hornblendite,
hornblende gabbro, and horn-
blende pyroxenite grading
internally into hornblende
norite. Strong igneous flow
layering defined by primary
prismatic amphibole
Resembles core rocks of Rose-
town pluton.

CENTRAL BASIN OF BALK

Pluton 5: (a) Biotite-horn-
blende norite and gabbro
with prismatic hornblende
forming crescent-shaped
pluton molded onto western
edge of central basin
with border facies of con-
taminated diorite-monzo-
diorite (b).

Pluton 5: (d) Coarse poiki-
litic hornblende norite,
(c) zone of nonlayered but
strongly flow laminated
coarse grained norite and
hornblende norite, (a) zone
of well layered, coarse and
fine grained norite with
strong igneous flow lamination
of plagioclase and hypers-
thene intruded by weakly
laminated sills of feldspathic
norite and monzodiorite (b);
xenoliths of Manhattan Schist
and calc-silicate rock are abun-
dant in zone (a).

EASTERN FUNNEL OF BALK

Pluton 6: Hornblende
pyroxenite, clinopyroxenite,
peridotite and hornblende
peridotite intrudes across
flow layering in rocks of
the central funnel. Resembles
rocks in pluton 4, 3 and the
ultramafic rocks at Rosetown.

Fanglomerate — JURASSIC AND TRIASSIC

~ Unconformity ~

Omb
Oma — Oml
Manhattan Schist — MIDDLE ORDOVICIAN

€i
Inwood Marble and
Lowerre Quartzite — LOWER ORDOVICIAN AND CAMBRIAN

~ Unconformity ~

€lp
Lowerre or Poughquag Quartzite — LOWER CAMBRIAN

Yhg
Ya
Basement gneiss
Yhg—Hornblende granite gneiss
Ya—Amphibolite — PROTEROZOIC Y

Igneous flow structure

Axial trace of upright
folds in Central funnel

U
—
D

Fault high angle, thrust, strike

Open work breccia in fault

Fig. 15. Explanation for Fig. 14, showing correlation of igneous
rocks of the Cortlandt Complex and Rosetown pluton
(from Ratcliffe and others, in press). Plutonic rocks are of
probable Late Ordovician age.

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A

ROCKS OF WESTERN BLOCK AND IGNEOUS ROCKS
COMMON TO BOTH BOOCKS

IGNEOUS ROCKS

Pegmatite

Yd

Diorite and dikes of
Canopus pluton

Canada Hill Granite[1]

Storm King Granite[1]

Yq

Oligoclase quartz gneiss

PARAGNEISS AND
VOLCANIC ROCKS

Rusty sillimanite schist

Calc-silicate rock and
magnetite deposits

PROTEROZOIC Z(?)

PROTEROZOIC Y

[1] Of New York State usage

CANOPUS PLUTON   WICCOPEE PLUTON

CANOPUS FAULT

12 KM

301

5 KM

Yb

Yd

Yb

Yd

Yb

12 KM

LAKE PEEKSKILL FAULT

CANOPUS FAULT ZONE IN LATE PROTEROZOIC
TIME SHOWING STEEPLY DIPPING ISOCLINALLY
FOLDED MAGNETIC ROCKS WEST OF FAULT

ROCKS EAST OF CANOPUS FAULT

Reservoir Granite

Yb

Layered biotite granite gneiss

Amphibolite and gabbro
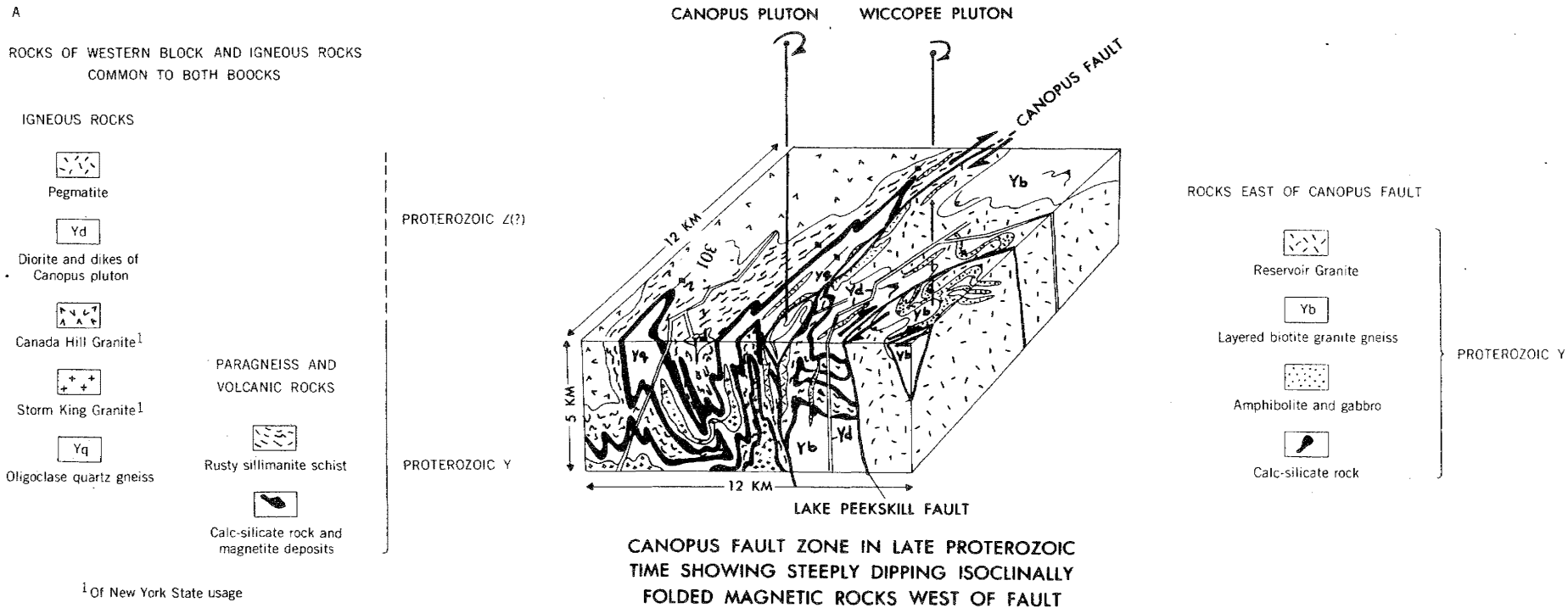
Calc-silicate rock

PROTEROZOIC Y

Fig. 16.   Generalized block diagrams showing the structural
evolution of the Ramapo-Canopus fault zone and location
of earthquake epicenters.

A.   Canopus fault zone in Proterozoic time showing two mafic
plutons, Canopus and Wiccopee, that are intruded
syntectonically with respect to Canopus and Lake Peekskill
faults. Crosscutting mafic dike of metadiabase or
ferrodolerite are probably of Proterozoic Z age and post-
date "Grenville" deformation.

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B

Peekskill Granite[1] } DEVONIAN(?)

Cortlandt Complex
Igneous rocks and dikes } UPPER ORDOVICIAN

Om

Manhattan Schist

Wappinger Limestone and
Poughquag Quartzite } MIDDLE·ORDOVICIAN TO CAMBRIAN

Unconformity

Canada Hill Granite[1]   Reservoir Granite
of eastern block[1]   Storm King Granite
of western block[1]

Amphibolite

Rusty schist

Yp

Quartz plagioclase gneiss

Yq

Oligoclase quartz gneiss

Yg

Biotite granite schist } PROTEROZOIC Y

[1] Of New York State usage

BASEMENT AFFECTED BY ORDOVICIAN CHLORITE
TO GARNET ZONE RETROGRESSION

SERICITE CHLORITE-EPIDOTE
OR ACTINOLITE IN
PHYLLONITE ZONES

BIOTITE-MUSCOVITE
BLASTOMYLONITE

HUDSON RIVER

ROSETOWN PLUTON
AND DIKES
ANCESTRAL RAMAPO FAULT ZONE

THIELLS FAULT

EASTERN FUNNEL OF
CORTLANDT COMPLEX

20 KM

ORDOVICIAN PHYLLONITE ZONES
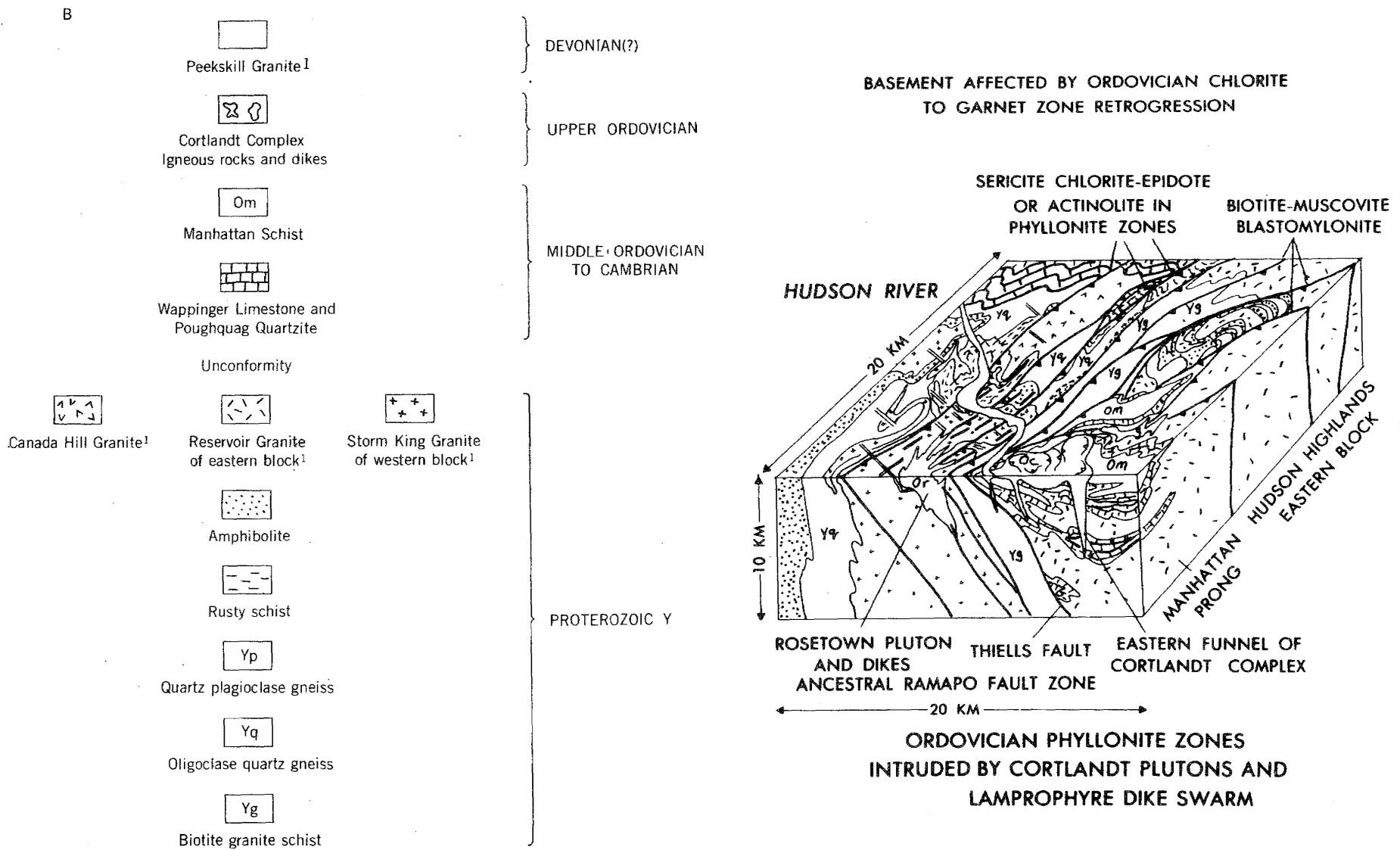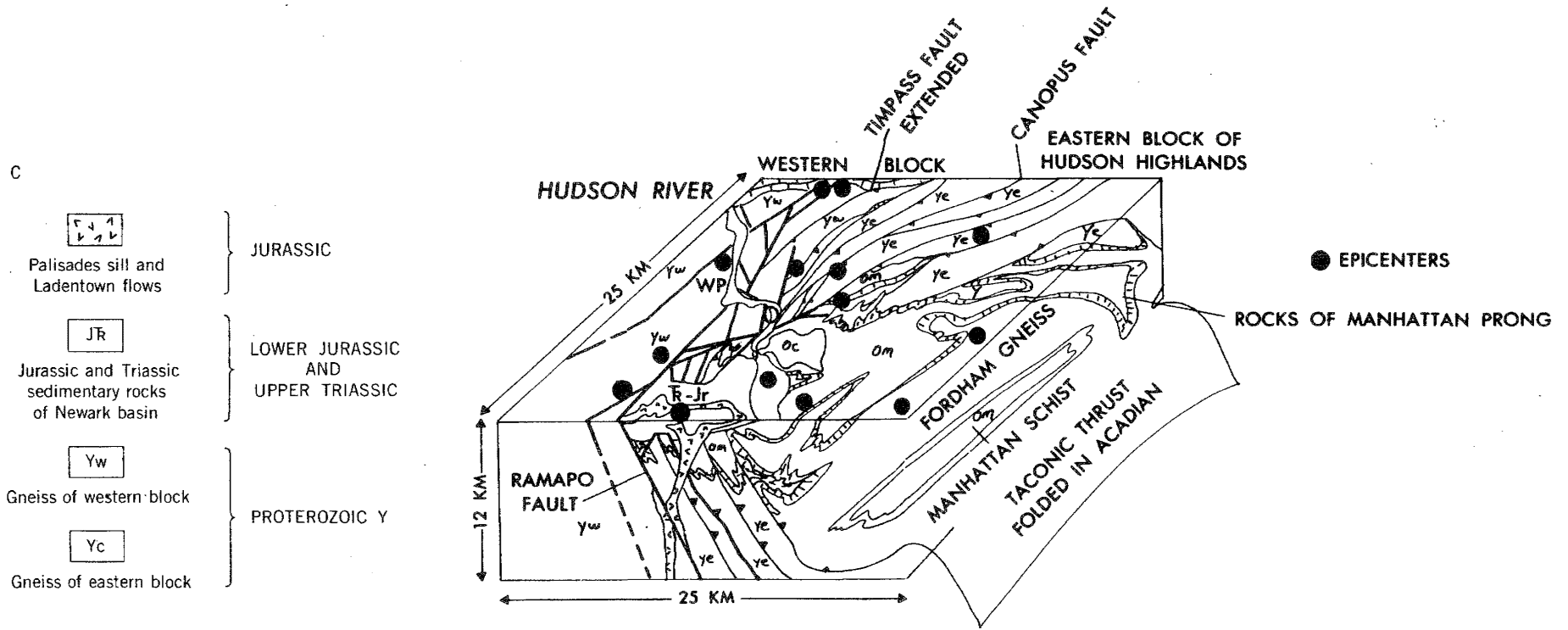INTRUDED BY CORTLANDT PLUTONS AND
LAMPROPHYRE DIKE SWARM

Fig. 16.   Generalized block diagrams showing the structural
evolution of the Ramapo-Canopus fault zone and location
of earthquake epicenters.

B.   Ramapo-Canopus zone in Late Ordovician time showing
retrogression of Proterozoic Y rocks in semiductile fault
zones to produce phyllonite and mylonite. Dike and plutons
of the Cortlandt Complex intrude along or crosscut these
faults.

C

Palisades sill and
Ladentown flows

JURASSIC

Jurassic and Triassic
sedimentary rocks
of Newark basin

LOWER JURASSIC
AND
UPPER TRIASSIC

Yw

Gneiss of western block

PROTEROZOIC Y

Yc

Gneiss of eastern block

HUDSON RIVER

WESTERN /BLOCK

TIMPASS FAULT EXTENDED

CANOPUS FAULT

EASTERN BLOCK OF
HUDSON HIGHLANDS

EPICENTERS

ROCKS OF MANHATTAN PRONG

RAMAPO FAULT

12 KM

25 KM

FORDHAM GNEISS

MANHATTAN SCHIST

TACONIC THRUST
FOLDED IN ACADIAN

RAMAPO-CANOPUS FAULT ZONE IN MESOZOIC TIME
SHOWING STEEPLY DIPPING OLD STRUCTURAL GRAIN
OF PROTEROZOIC AND ORDOVICIAN AGES

Fig. 16.   Generalized block diagrams showing the structural
evolution of the Ramapo-Canopus fault zone and location
of earthquake epicenters.

C.   Ramapo fault zone in Early Jurassic time showing steep
attitude of older grain and distribution of earthquake
epicenters. Heavy lines represent Mesozoic faults. Note
absence of Mesozoic faults in area of epicenters northeast
of Hudson River where earthquakes appear to be spatially
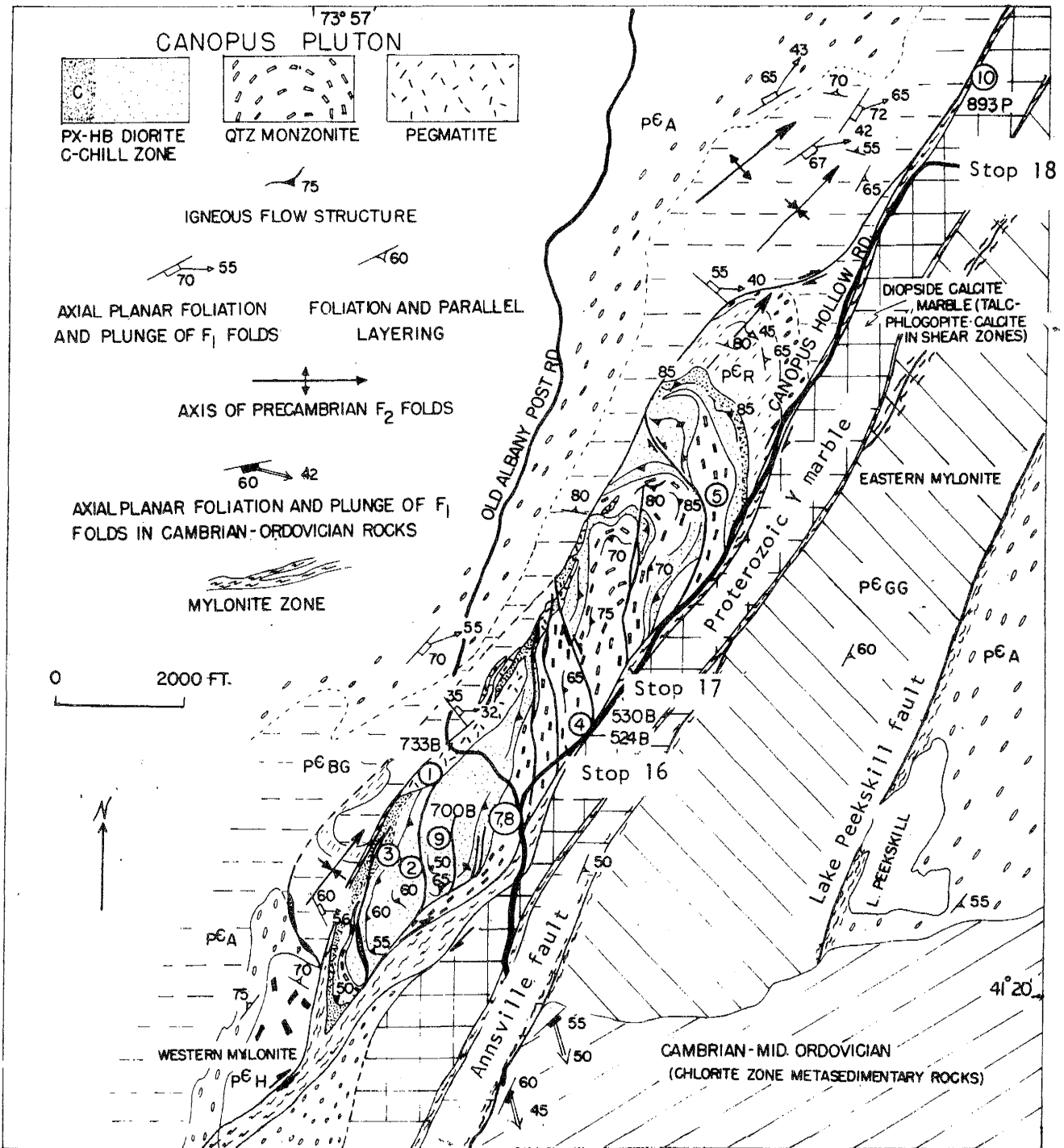related to steep zones of semiductile faulting.

Fig. 17. Geologic map of the extension of the Ramapo-Canopus fault zone showing location of Stops 16, 17, and 18. Generalized geologic map of the Canopus pluton, showing internal igneous flow structure and relationship of pluton to F₁ and F₂ structure in Proterozoic gneisses. Key to Proterozoic lithologies; pCA = amphibolitic gneiss, pCGG = granodioritic gneiss, pCBG = biotite quartz plagioclase paragneiss, pCR = rusty weathering granitic gneiss, pCH = hornblende-biotité granitic gneiss. K-Ar and Rb-Sr ages are shown on map. (B = biotite, P = phlogopite). Numbered localities on sample sites for whole rock and mineral data. Underlined dates refer to K-Ar, other date Rb-Sr from Ratcliffe and others (1972). Figure reprinted from Ratcliffe and others (1972).

The "GIANT'S CAUSEWAY"
at Orange, N.J.
by
Charles Graham, 1884