William J. Cahill, Jr.
Vice President

Consolidated Edison Company of New York, Inc.
4 Irving Place, New York, N Y 10003
Telephone (212) 460-3819

January 19, 1976

Re Indian Point Unit No. 3
Docket No. 50-286

RECEIVED
JAN 19 1976
U.S. NUCLEAR REGULATORY COMMISSION
Mail Section

Mr. D. B. Vassallo, Chief
Light Water Reactors
Project Branch 1-1
Division of Reactor Licensing
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Dear Mr. Vassallo

As discussed with members of the NRC staff on December 10 and 11, 1975 and as requested by your letter dated January 8, 1976, forwarded herewith please find forty (40) copies of a supplement to the Dames & Moore report, "Supplemental Geological Investigation of the Indian Point Generating Station", transmitted to Mr. DeYoung on December 5, 1975. This supplement includes the review panel's evaluation report. Additionally, forty (40) copies of an interim report prepared by Professor Ratcliffe addressing regional faulting are also forwarded.

These two documents provide all the additional documentation and supporting data requested by your January 8, 1976 letter.

Very truly yours

William J. Cahill, Jr.
Vice President

enc.
mk

Sworn to before me this
19th day of January, 1976.

ANTONIO MONTEAVARO
Notary Public State of New York
No. 03-9830696
Qualified in Bronx County
Term Expires March 30, 1976

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Closter Road
Palisades, New York 10964
January 11, 1976

Rec 1 w/ltr dtd 1-19-76

DOCKETED USNRC JAN 19 1976 U.S. NUCLEAR REGULATORY COMMISSION Mail Section

Mr. Victor Gonnella
Consolidated Edison Company
4 Irving Place, Room 1028
New York, New York 10003

Dear Victor:

In reply to your request for information regarding point 8 in the request for additional information from NRC dated January 8, I thought it best to transmit something brief that I had written rather than letting you interpret my reply or abstract. Would you therefore just transmit the enclosed material in its entirety to NRC. I wish that you would not condense, paraphrase, or otherwise reinterpret any of this material under my name for any purpose. It is understood that all statements contained herein are preliminary and are subject to change as new data are assessed.

Since my June 1975 report, I have some new and important data that suggest that the N. 10° E., N. 40° E. trending fault system that extends from Thiells, N.Y., to Tomkins Cove, generally referred to as the extension of the Triassic border fault (Ratcliffe, 1971, Figs. 1 and 3), probably is Paleozoic (pre-Triassic) in age. Data from two localities are presented below. An index map Fig. 1 (Fig. 2 in the 1971 reprint) shows the location. I prefer to use this map rather than release a preliminary and incomplete geologic map at 1 : 24,000 at this time.

Locality 1: Thiells fault exposure

Cambrian Poughquag Quartzite is in fault contact with Grenville gneiss, Fig. 2. At this contact a greenish-gray, nearly monomineralic muscovite (sericite) rock is found. Thin section textures indicate replacement of quartz with deformation lamellae, by fine-grained nonalligned muscovite, apparently caused by hydrothermal alteration along the fault. Thin section examination of numerous samples from this zone shows no evidence of post-replacement deformation, although the muscovitic rock in the fault zone contains well developed slickensides. Analytical data for a muscovite-rich rock from this fault zone are given in Fig. 3. X-ray diffraction data indicate that the analyzed material is almost entirely muscovite with the traces of quartz. Alkali feldspar, plagioclase, or chlorite are not present in detectable amounts.

Petrographic examination of thin sections of the rock material sampled for dating is approximately 95 percent fine grained white mica "sericite" with small remnants of partially replaced quartz. Progressive replacement textures from pure quartzite to 95 percent replacement by muscovite are recorded in thin sections, suggesting large scale introduction of K, Al and H_2O into the fault zone. The fine grained sericite is nonoriented and shows no evidence of deformation subsequent to replacement crystallization.

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I conclude from these relationships that at the locality sampled (the 5-10 ft. muscovite-rich replacement zone) no displacements subsequent to the age of crystallization of the muscovite have taken place. The 379 ± 13 m.y. K-Ar age, therefore, suggests that the fault is at least this old.

Because the regionally metamorphosed Middle Ordovician Annsville Phyllite is offset to the north, the fault must be younger than the regional metamorphism at 400-450 m.y. (Ratcliffe, 1971) but must predate the seritization in the Cambrian rock at 379 m.y. Therefore the Thiells fault is interpreted as a Late Ordovician or Silurian fault. Structural relationships suggest that this may be a normal fault with a component of left lateral movement, or a thrust fault with a component of right lateral movement.

The muscovite age and textural observations suggest a minimum age for the fault zone, but the data do not preclude more recent movement on other surfaces in the outcrop.

Precambrian gneiss of the footwall is a black ultramylonite with a thin zone of possible pseudotachylite at the actual fault. To the north this kind of distinctive cataclastic rock characterizes the footwall of the border fault. The K-Ar muscovite age therefore serves as a minimum age for this cataclasis. Since no change in character of cataclasis exists in the footwall rocks of the border fault from Thiells to Tomkins Cove, I conclude that the ultramylonites are all coeval and are older than the 379 ± 13 m.y. muscovite age at Thiells.

Locality 2:

Locality 2 is a newly discovered exposure of the Triassic unconformity (Fig. 1). Here limestone fanglomerate rests on sheared and mineralized Annsville Phyllite (actually a metasiltstone with regional metamorphic biotite and sericite). Petrographic examination of the sheared and microfaulted phyllite immediately beneath the exposed unconformity contains abundant vein and fracture filling material rich in clinozoisite, chlorite-quartz, and possibly potash feldspar. X-ray diffraction data support the presence of all the above minerals except K-feldspar, which may be nondetectable in small qualtities. The conglomerate illustrated in Fig. 4A,B contains fragments of faulted Annsville, but the matrix of the conglomerate is nonfaulted and lacks the secondary mineralization found in the Annsville beneath the unconformity.

Attempts to recover spores possibly diagnostic of a Triassic age from conglomerate matrix failed. Only traces of highly oxidized organic material were recovered. Despite the lack of paleontologic data, the lithified nature of the conglomerate, the presence of angular clasts of Ordovician marble and phyllite similar to those found in the Triassic fanglomerate, and the proximity to similar Triassic fanglomerate suggest to me that the conglomerate is "Triassic." However, the gray color of the conglomerate differs from that of the bulk of the red "Triassic" fanglomerate nearby. Gray, basal limestone conglomerates are known from the Gettysburg

Basin in Pennsylvania. Therefore I regard the conglomerate as Late Triassic or Jurassic in age.

The phyllite exposure and the unconformity lie east of the "Triassic border fault" Fig. 1. Triassic is not exposed in contact with Precambrian at any locality along the border fault from Thiells north to Tomkins Cove, so sedimentary onlap across the border fault is not demonstrable, but neither is faulting of Triassic rocks. Contrary to my previous interpretation (Ratcliffe, 1971, Figs. 3 and 4) and that of the preliminary report to Con Ed June 1975, the contact between Triassic and other rocks in Fig. 3 (1971) is now interpreted as an unconformity based on the observations at locality 2 and the mapped contacts of the Triassic rocks.

The age of the mineralization and faulting at locality 2 is not known. However, a ≈400 m.y. whole rock K-Ar age on phyllite was reported by Dames and Moore from this locality for a rock that contains a prefault foliation outlined by muscovite and biotite. I judge that the 400 m.y. whole rock age approximately dates the Late Ordovician-Silurian regional metamorphism. This whole rock age is consistent with the 380 m.y. muscovite age at Thiells (locality 1), and both the clinozoisite-chlorite mineralization at (2) and muscovite at (1) could have formed in the same late hydrothermal Paleozoic event. This faulting and mineralization may have been related to late stage Taconian adjustments following evacuation of the Cortlandt magma chamber or could be related to a distinctly different Acadian event.

It is unlikely that the mineralization in the phyllite at locality 2 is Triassic or younger in age because the mineralization is lacking from the overlying conglomerate and it would not have formed under low temperatures at the earth's surface.

In summary, the new observations at localities 1 and 2 suggest that the western margin of the Triassic basin previously known as the Triassic border fault at the northern end of the Newark Basin has fault fabrics and structures related to faulting of probable Paleozoic age. Movement on these faults in Triassic or younger time is not required by any data that I now have. This does not, however, rule out the possibility of localized reactivation that thus far is undetected.

Attached is a copy of an abstract I have submitted to N.E. Section Meeting of G.S.A. for presentation in March. It expresses the same ideas as above but stated in a different way. Abstracting or paraphrasing from the abstract should be avoided.

I hope this answers question 8 for the present.

Sincerely,

Nicholas Ratcliffe

Nicholas M. Ratcliffe

Fig 2.

KRUEGER ENTERPRISES, INC.
GEOCHRON LABORATORIES DIVISION
24 BLACKSTONE STREET • CAMBRIDGE, MA. 02139 • (617)-876-3691

POTASSIUM-ARGON AGE DETERMINATION — REPORT OF ANALYTICAL WORK

Our Sample No. R-3409

Date Received: 6 October 1975

Your Reference: PK 764 A J.O. 0874047

Date Reported: 17 October 1975

Submitted by: Thomas E. Mills
Dames & Moore
6 Commerce Drive
Cranford, NJ 07016

Sample Description & Locality: Fine grained greenish-gray sericite(?) schist, sample PK 764 A. Chips taken from each of the three pieces and made into a composite for analysis.

Material Analyzed: Whole rock, -60/+200 mesh.

Ar^{40*}/K^{40} = .02456

AGE = 379 ± 13 M.Y.

Argon Analyses:

Ar^{40*}, ppm.	Ar^{40*}/ Total Ar^{40}	Ave. Ar^{40*}, ppm.
.2618	.984	.2611
.2604	.982	

Potassium Analyses:

% K	Ave. %K	K^{40}, ppm
8.693	8.715	10.632
8.737		

Constants Used:

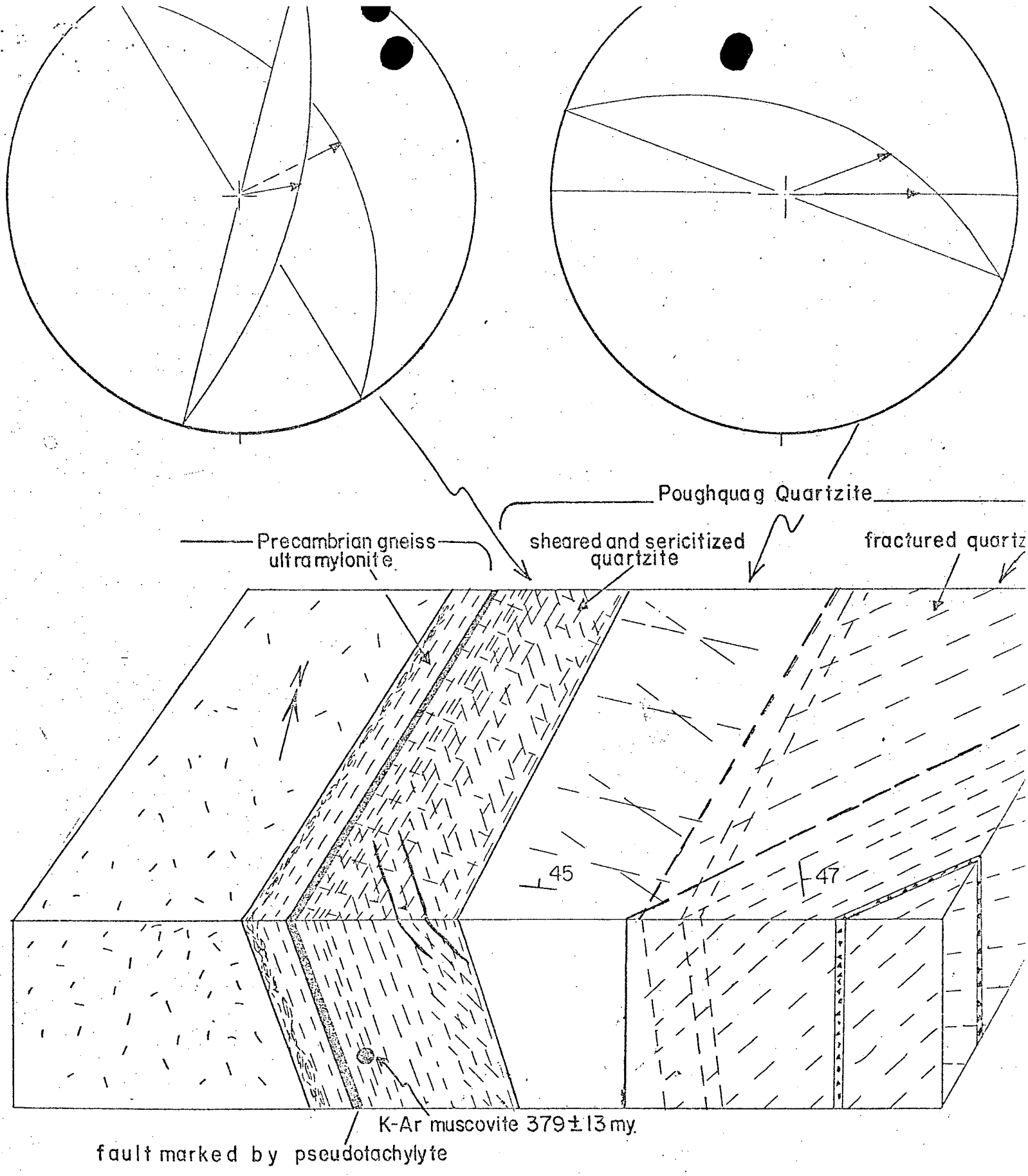
$\lambda_\beta = 4.72 \times 10^{-10}$/ year

$\lambda_e = 0.585 \times 10^{-10}$/ year

$K^{40}/K = 1.22 \times 10^{-4}$ g./g.

$$AGE = \frac{1}{\lambda_e + \lambda_\beta} \ln\left[\frac{\lambda_\beta + \lambda_e}{\lambda_e} \times \frac{Ar^{40*}}{K^{40}} + 1\right]$$

Note: Ar^{40*} refers to radiogenic Ar^{40}.
M.Y. refers to millions of years.



Fault zone Thiells, N.Y. PK 764

Figure. 2 Block diagram of fault at Thiells, N.Y., showing intensely developed zone of ultramylonite, and pseudotachylyte at contact of Cambrian Poughquag Quartzite and Precambrian 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. 1" ≈ 10'

Lower hemisphere equal area projections of dominant shears in three areas above, and common slickenside plunges are shown. The concentration of slip direction in the northeast quadrant, together with the stratigraphic displacement suggest that the main fault is an east-dipping normal fault with a small component of left lateral strike slip movement.

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 Silurian in age and is therefore regarded as a Taconic fault.

See Fig 1 (Ratcliffe 1971 p. 128) for location

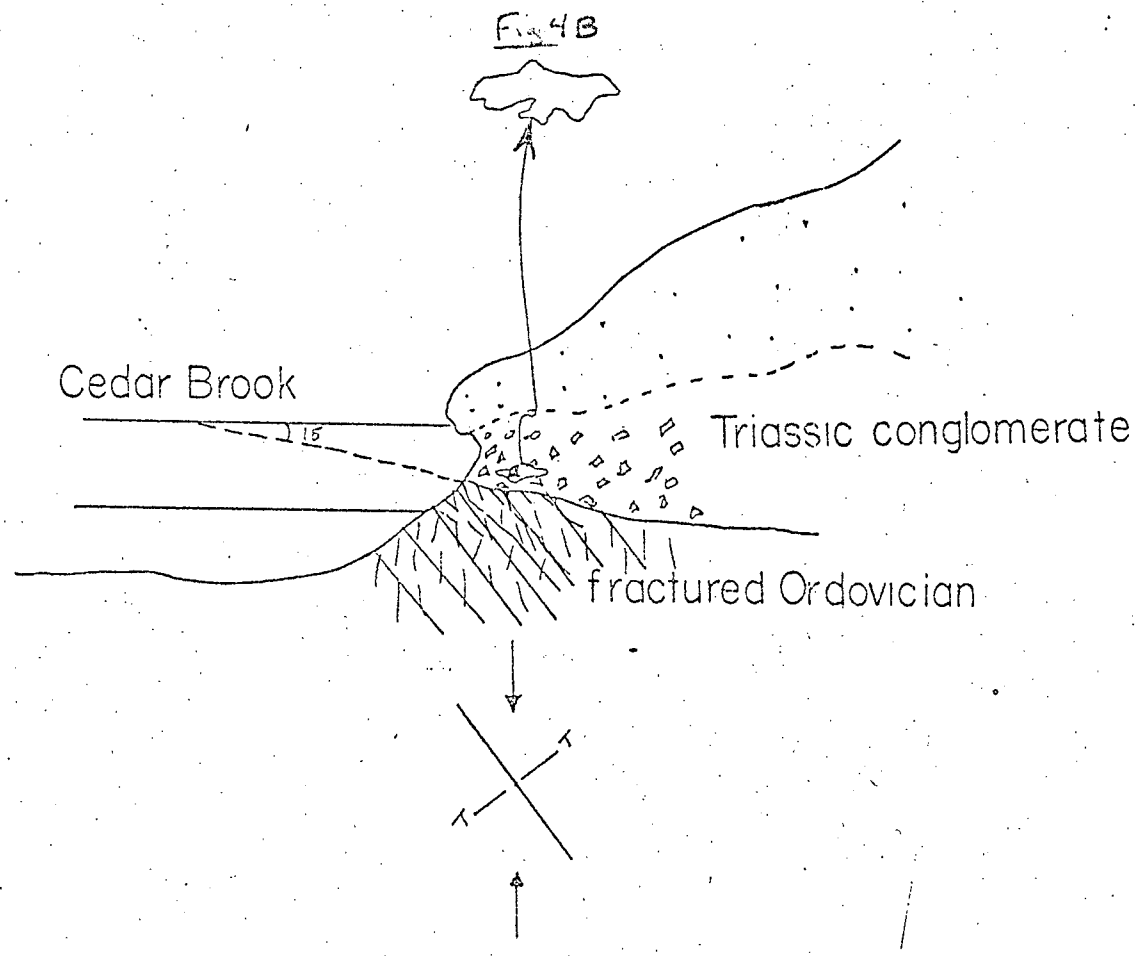


Figure 4A. Cross section of Cedar Brook locality showing unconformable contact between grey to yellow-tan carbonate fanglomerate of probable Triassic or Jurassic age resting on brecciated Ordovician metasiltstone. The lower 10 cm of fanglomerate consists of nearly monomict breccia of immeidately underlying fractured metasiltstone. Ten cm above contact angular fragments of beige dolostone, blue-gray calcite dolostone (Wappinger Limestone) and black metasiltstone predominate. Exotic chips of hornblende granite gneiss are found. The exposed thickness of the carbonate-rich fanglomerate is 1.5 m. The unconformity strikes N. 40° E. and dips 10-15° to the southeast. Dominant fracture directions in the metasiltstone are N. 43° 50° SE. and N. 10° E. 90°. The fanglomerate is unsheared in these directions.

1" = 10'

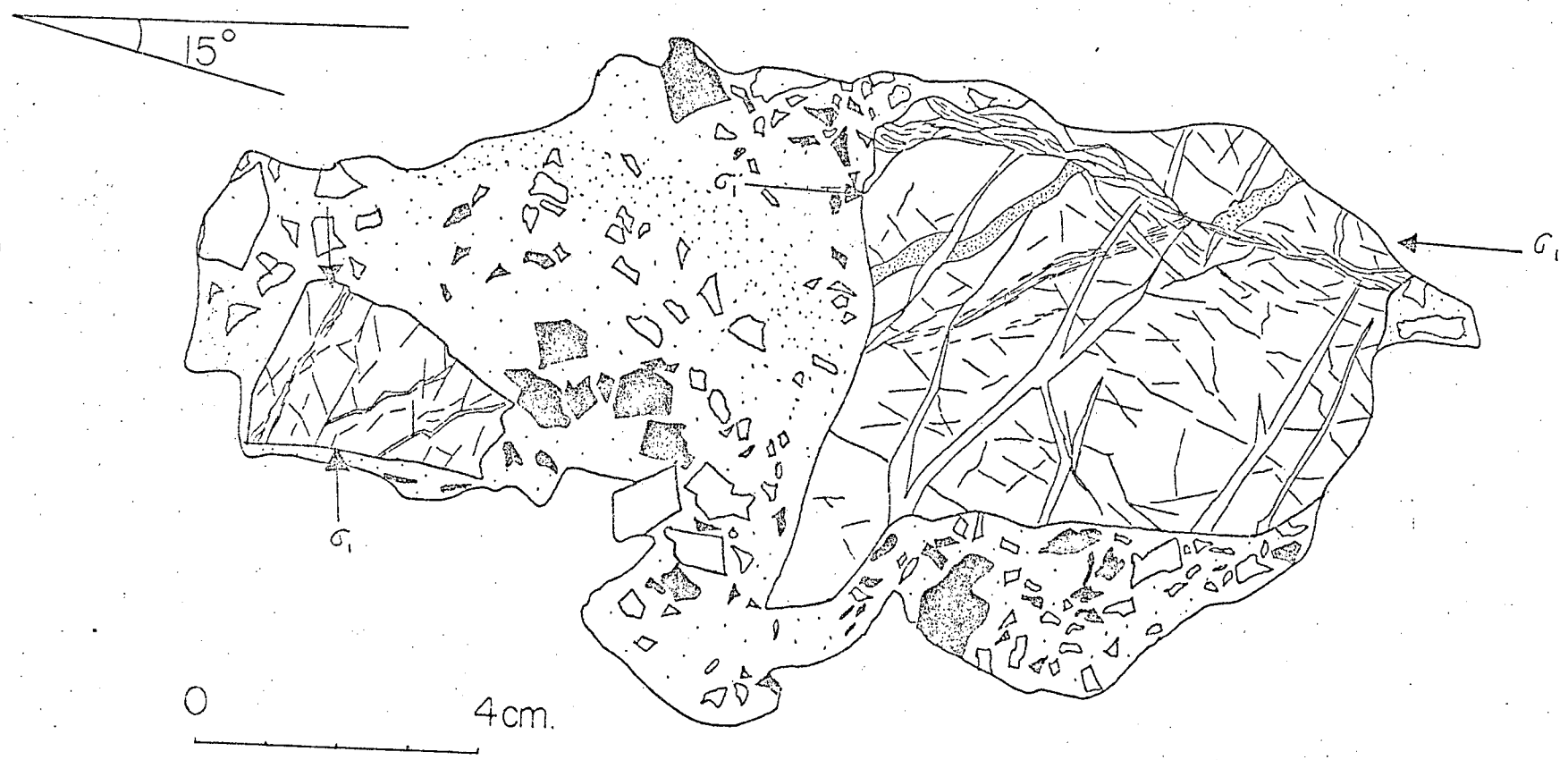


Figure 2B. Sketch of a hand specimen of fanglomerate taken approximately 0.5 m above unconformity, showing brecciated clasts of Wappinger in nonsheared Triassic matrix. The 15° dip to southeast is identified. Black fragments are Ordovician metasiltstone, clear clasts are predominantly beige to gray dolostone (Wappinger fragments), the matrix of the fanglomerate is 1 - 0.5 m fine carbonate and quartz sandstone.

Two highly fractured angular clasts of blue-gray calcitic dolostone are shown in the specimen. The larger clast contains two dominant shear directions, one of which dips gently to southeast, the other dips moderately steeply to the northwest. A 0.5 cm marker bed is offset 2 cm in a right lateral sense along the shallow shear. Calcite filled tension fractures are shown approximately normal to the two shears. Note the lack of brecciation and of offset in the matrix, the faulting and brecciation predated encorporation in conglomerate.

The second clast contains similar cataclastic texture seen in clast 1, but the shear directions are differently oriented. Matrix of conglomerate is not sheared. Principal compressive stresses accounting for brecciation of two pebbles do not agree with one another, and neither agrees with fabric in brecciated rock immediately beneath unconformity.

PALEOZOIC AGE OF "TRIASSIC" BORDER FAULT AT NORTHERN END OF NEWARK BASIN IN NEW YORK STATE

Ratcliffe, Nicholas M., Department of Earth and Planetary Sciences, City College of C.U.N.Y., New York, New York 10031

Muscovite from highly sheared and sericitized Lower Cambrian Poughquag Quartzite in fault contact with Precambrian granitic gneiss at Thiells, N.Y., near the border of the Triassic Newark Basin has yielded a 379 ± 13 m.y. K-Ar age. Replacement textures within the fault zone show that the muscovite postdated shearing in the fault zone and has not been subsequently deformed. The fault, which strikes N. 15° E. and dips 65° SE., is strongly slickensided with down dip lineation, and is interpreted as a normal fault. Map relationships indicate that the dated fault is one segment of a set of N. 10° E. and N. 40° E. normal faults that appear to form the northwest margin of the Triassic Newark Basin, although Triassic rocks are nowhere displaced. Fanglomerate of the basal Triassic unconformably overlies cataclastic Ordovician phyllite of the fault zone and contains cobbles of cataclastic phyllite and of Cambro-Ordovician limestone. These data indicate that the intense cataclasis (pseudotachylyte and ultramylonite) in Precambrian and Paleozoic rocks adjacent to the "Triassic" border fault is Ordovician or Silurian in age rather than Triassic as expected. The fault may have formed in response to crustal subsidence relatdd to evacuation of the Cortlandt magma chamber. Clear evidence for Triassic faults bounding the Basin is lacking, and sedimentary onlap accounts for the northern termination of Triassic rocks of the Newark Basin.

Nicholas M. Ratcliffe

Abstract submitted to N.E. Section meeting of G.S.A., to be held in Washington, March 1976.

212-690-6934

NICHOLAS M. RATCLIFFE *Department of Geology, City College of City University of New York, New York, New York 10031*

The Ramapo Fault System in New York and Adjacent Northern New Jersey: A Case of Tectonic Heredity

ABSTRACT

The Ramapo fault system forms the northwestern boundary of the Newark Triassic basin in New York and adjacent northern New Jersey, and is commonly attributed to Mesozoic crustal fracturing. However, the detailed geology in the vicinity of this fault indicates an earlier, complex tectonic ancestry, perhaps dating from late Precambrian time. Intense cataclastic effects found in Precambrian to Middle Ordovician rocks on both sides of the Ramapo fault are absent from the bordering Triassic rocks of the footwall block. Significant post-Middle Ordovician right-lateral-transcurrent faulting is recorded by actual offset of distinctive units and by the megascopic fabric in mylonite zones. The total cumulative offset since the late Precambrian on these faults is unknown but could be large. Right-lateral displacement of 4 km is indicated for the Canopus Valley area. Intrusive relationships of probable late Precambrian to Late Ordovician diorite plutons and dikes, as well as pegmatites of probable Devonian age, help date the strike-slip movements as Paleozoic and older.

Block faulting along the Ramapo fault in the Lower Ordovician affected Middle Ordovician sedimentation and resulted in unconformable relationships between a Middle Ordovician gneiss-boulder conglomerate (Bucher, 1957) and Precambrian gneisses on the upthrown block west of the fault north of Peekskill, New York.

Repeated movements of the Highlands block during Late Triassic time produced the coarse clastic fanglomerates of the Hammer Creek Formation adjacent to the Ramapo fault. This syndepositional faulting was followed by post-Brunswick downdropping along the Ramapo fault south of the Hudson River. Recent seismic activity along this fault system reported by Page and others (1968) suggests that the fault may still be active. These observations suggest a possible tectonic longevity of some 700 m.y. for the "Triassic" border fault system here.

This fracture system had deep crustal connections along which basic magma rose toward the surface in Late Precambrian, Late Ordovician (Cortlandt), and Late Triassic time (Palisades sill and Triassic flows). The Ramapo fault also marks the boundary between tectonic blocks having different Paleozoic deformational histories. These observations, along with the remarkable longevity, suggest that this fault zone may be part of a fundamental crustal fracture system that was operative during formation of the Appalachian orogen.

The ideas presented here require a degree of tectonic permanence not commonly reported in orogenic belts. Activity along this fracture system in pre-Middle Ordovician time as documented here suggests strongly that the northern end of the Reading Prong is not allochthonous in the sense proposed by Isachsen (1964).

INTRODUCTION

The Triassic basin of New Jersey and New York (Newark basin) is a half-graben bordered on the northwest by a northeast-trending system of irregularly developed high-angle faults (Sanders, 1963; Van Houten, 1969). Although the Precambrian rocks of the footwall commonly have contacts with the downdropped Triassic, locally Paleozoic (Cambro-Ordovician) rocks lie adjacent to the border faults on the east (Bayley and others, 1914; Drake and others, 1961). Depositional, nonfaulted contacts of Triassic rocks lapping onto Paleozoic or Precambrian rocks along the western and northern margin of the Newark basin have been cited (Drake and others, 1961;

Geological Society of America Bulletin, v. 82, p. 125–142, 5 figs., January 1971

Van Houten, 1969; Ratcliffe, 1968a, p. 200). Thus the northwestern boundary of the Newark basin Triassic, although commonly referred to as the Triassic border fault, actually is comprised of many closely spaced separate subparallel faults that commonly trend N. 30° to N. 50° E. This consistency in trend, except where later northwest-trending cross faults such as those near Flemington, New Jersey, offset the border faults (Sanders, 1963), gives the impression of a rather continuous fault on regional compilations shown at a small scale (for example, Sanders, 1963, Fig. 7). The term "border fault system" will be used to describe collectively these various faults that either mark the northwest border of the Triassic sediments or lie close to the depositional edge of the basin.

In northern New Jersey and southeastern New York State, the border fault system is expressed by a fairly straight fault trace marked by the topographic escarpment of the Ramapo Mountains for which the fault is named. The Ramapo fault proper extends from Stony Point, New York, on the Hudson River, southwest approximately 50 mi to Peapack, New Jersey (Fig. 1). Banked against the fault are coarse deposits of Triassic conglomerate containing abundant clasts of dolostone and metaquartzite thought to have been locally derived by uplift and erosion of the Paleozoic cover of the Hudson Highlands during Late Triassic time (Carlston, 1946; Savage, 1968). At the northern end of the Triassic basin near Stony Point, New York, the Triassic rocks probably rest unconformably on Paleozoic rocks (Ratcliffe, 1968a, p. 200) rather than being downfaulted along an east-west fault as shown by Fisher and others (1962) and Savage (1968). At this point, the Ramapo fault downdrops both Triassic and Paleozoic rocks against the Precambrian on the west. This fault extends across the Hudson River to the Peekskill Hollow area where Paleozoic rocks (Annsville Phyllite–Middle Ordovician) rest against Precambrian gneiss (Berkey and Rice, 1919; Ohan, 1964). From Annsville, a complex fracture zone along Canopus Creek extends northeasterly across the entire width of the Hudson Highlands locally, bringing Paleozoic rocks ("Trentonian" Limestone; *see* Bucher, 1957) or the Poughquag Quartzite of Early Cambrian age in juxtaposition with older rocks (Berkey and Rice, 1919; Gordon, 1911) (Fig. 1). The Ramapo fault proper and its northern extension into the Hudson Highlands of New York are here referred to collectively as the Ramapo fault system.

The extension of this fault system from New Jersey across the Hudson River to the northeast into the Highlands of New York was suggested by Berkey and Rice (1919) and appears to be well substantiated (Bucher, 1957; Paige, 1956; Ohan, 1964).

The Ramapo fault system west of the Hudson River clearly underwent repeated movements in the Late Triassic, as recognized by other workers (Carlston, 1946; Sanders, 1963; Van Houten, 1969). However, estimates of the maximum dip-slip displacement on the border fault in New Jersey in post-Brunswick time range from 30,000 ft (Sanders, 1963, p. 510) to 18,000 ft (Van Houten, 1969, p. 328).

Sanders' recent synthesis of Triassic tectonism (1963), which summarizes much of the earlier work by that author and others, suggests that Triassic deformation was much more extensive and complex than previously realized. According to Sanders (1963, Fig. 2), the initial phase of Triassic subsidence extended over a single belt 50 to 70 mi wide, covering broad areas of southern Vermont, western Massachusetts, western Connecticut, and southeastern New York and New Jersey. The single depositional basin (the broad-terrane hypothesis) was modified by longitudinal crustal warping of 30,000 ft and subsequent erosion to produce the now isolated Massachusetts-Connecticut and Newark basins. The northern termination of the Newark basin at the Hudson River (Stony Point) (Fig. 1) was ascribed to the effects of a transverse upwarp known as the Danbury anticline, said to have 30,000 ft of structural relief (Sanders, 1960, p. 129; 1963, p. 510). An important corollary of Sanders' hypothesis is that the fault system that produced the initial Triassic graben subsidence and later post-Brunswick faulting should extend northeastward beyond the present limits of the Newark basin along the Ramapo fault. According to Sanders, Triassic rocks are not preserved along this fault owing to erosion produced by uplift on the Danbury anticline (1963, p. 518).

There is considerable evidence cited in the present paper that the Ramapo fault system does extend into the Hudson Highlands east of the Hudson River. However, the differential movement and igneous activity that took place along this fracture zone appears to be pre-Triassic in age. Many of the intense deformational effects along this ancient fracture system are here attributed to severe cataclasis along

deep-seated, right-lateral, late Precambrian and Paleozoic transcurrent faults. To what extent Triassic or younger faulting modified the geologic relations along the fracture zone is uncertain. However, there does not appear to be any direct evidence of Triassic or younger movement east of the Hudson River. In the opinion of this author, Triassic movement was rather limited along the northern trace of the Ramapo fault system. These ideas conflict

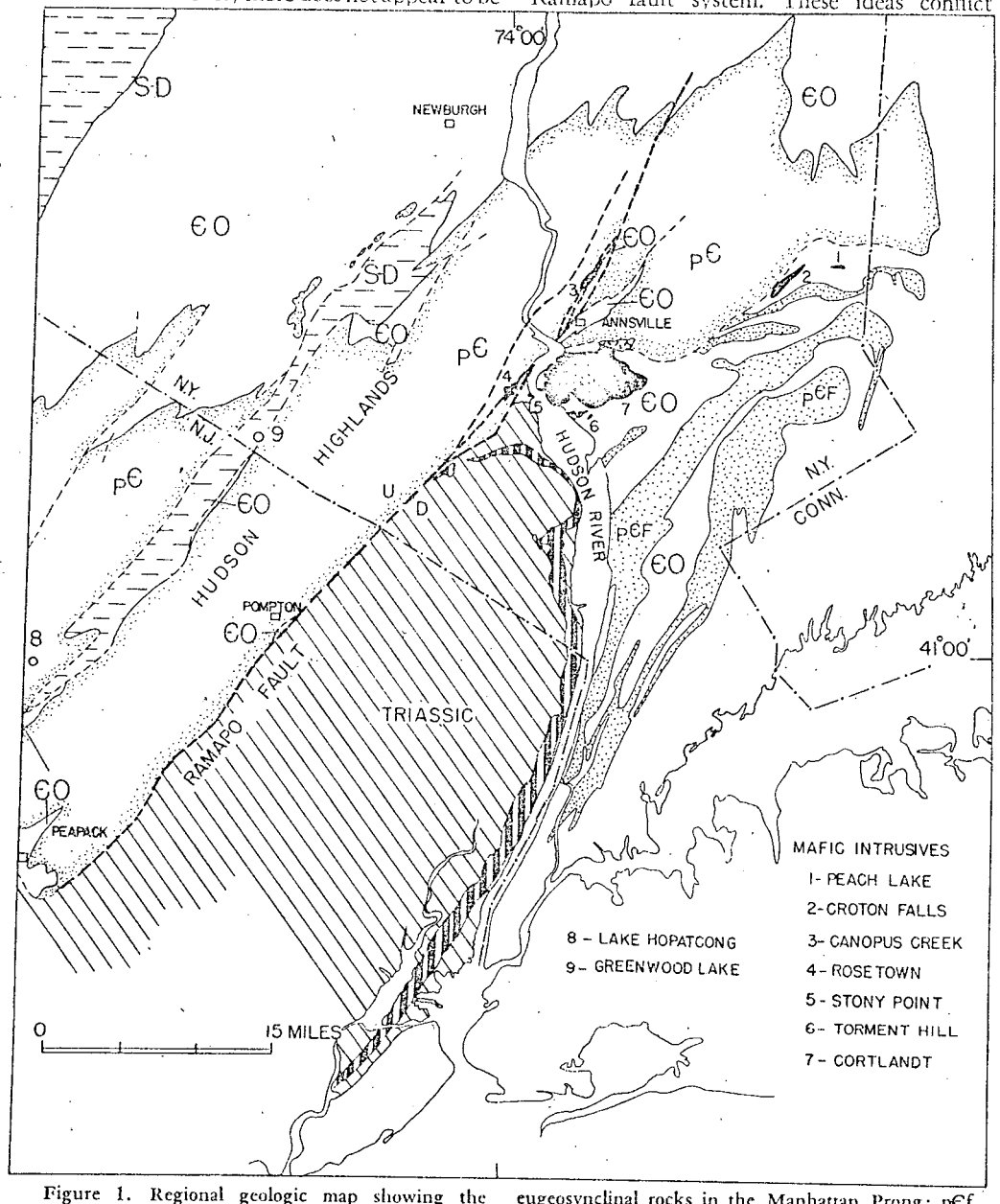


Figure 1. Regional geologic map showing the northern end of the Newark basin, the Ramapo fault and its possible extensions into the Hudson Highlands, as well as mafic intrusive centers of probable late Precambrian and Late Ordovician-Early Silurian age. S-D, Silurian and Devonian rocks; Є-O, Cambrian and Ordovician metasediments, including shelf and eugeosynclinal rocks in the Manhattan Prong; pЄf, Fordham Gneiss of probable Precambrian age; pЄ, gneisses of the Hudson Highlands Massif. Numbered localities are referred to in text. Heavy dashed lines show faults considered part of the Ramapo fault system; light dashed lines show other high-angle faults in the Hudson Highlands.

in general with the broad-terrane hypothesis espoused by Sanders (1963) regarding the extent of the original Triassic basin and suggest that the Danbury anticline proposed by Sanders (1960, p. 129) may not be required by the geologic data.

The purpose of this paper is not to deny the importance of Triassic faulting but to suggest that the crustal fractures along which Triassic rocks were downdropped were present as zones of dislocation as long ago as the late Precambrian or Early Paleozoic. Reactivation of these faults at various times in the geologic past is thought to be responsible for the complex deformational effects seen in Paleozoic and Precambrian rocks adjacent to the Ramapo

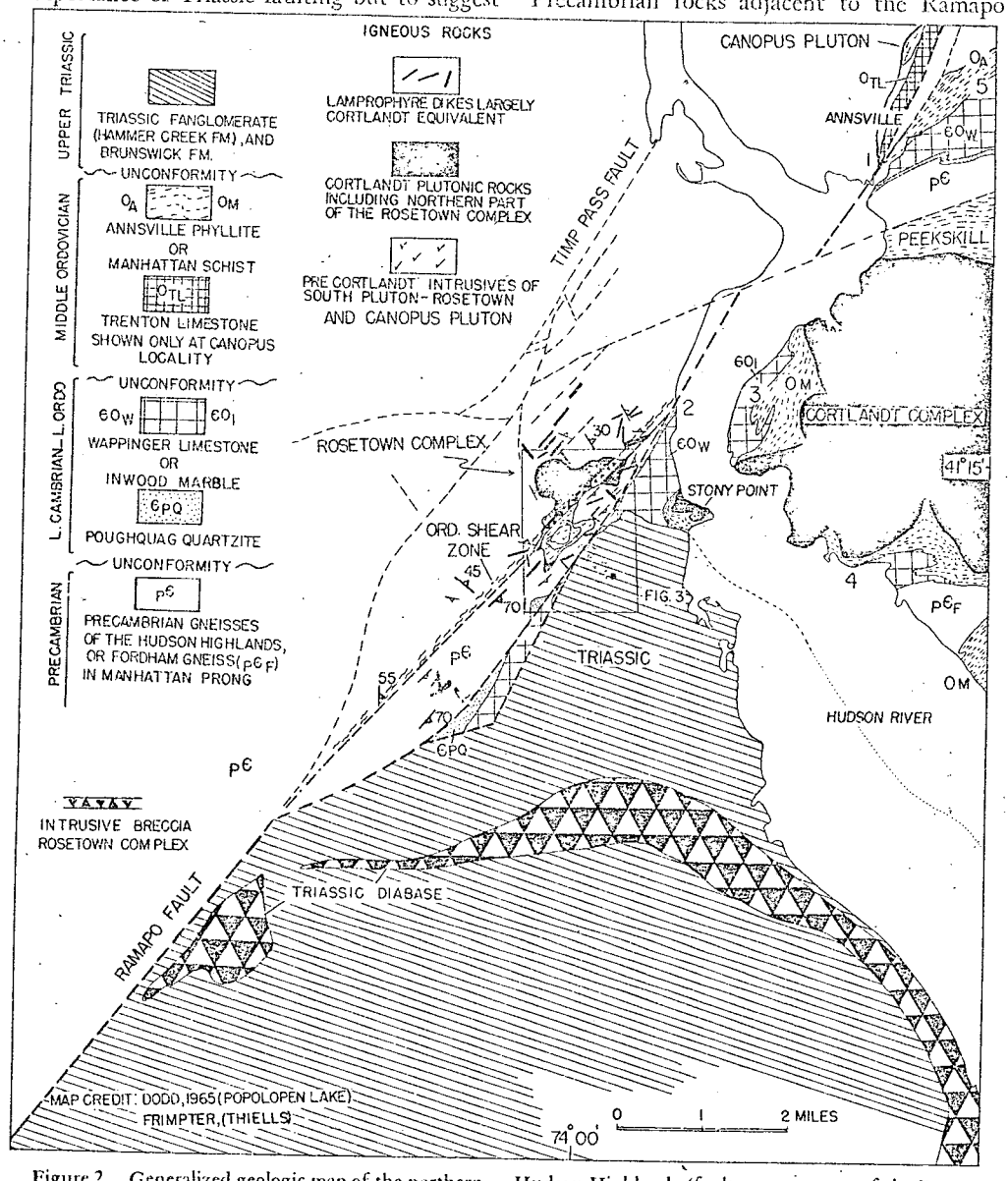


Figure 2. Generalized geologic map of the northern end of the Newark basin, showing the relationship of the Ramapo fault system to the Rosetown and Canopus plutons. Heavy lines signify faults of the Ramapo fault system; fine dashed lines other high-angle faults in the Hudson Highlands (fault patterns west of the Ramapo fault *from* Dodd, 1965, [Popolopen Lake quadrangle] and Frimpter, 1967). See Figure 3 for location of quadrangles.

1. Thiells fault

2. Triassic unconformity

fault and along the northeastern projection of this fault in the Hudson Highlands.

The idea that pre-Triassic movement occurred on the Ramapo fracture system was suggested by Berkey and Rice (1919, p. 116). Recent information, however, comes from several different areas of investigation, summarized in the following: (1) study of the physical nature of the cataclasis exposed in fault zones bordering the Triassic; (2) relationship of the fault system to zones of deep erosion during Middle Ordovician time and study of the facies of the limestone deposited immediately above the Middle Ordovician unconformity; (3) study of igneous rocks of probable late Precambrian to Ordovician or Early Silurian age that have intruded fracture zones in the footwall block parallel to the adjacent downdropped Triassic blocks; (4) nature of the Triassic sediments and depositional environment adjacent to the border faults during Late Triassic time.

These various lines of evidence indicate that the geologic history of the rocks in the vicinity of the Ramapo fault has been complex. Evidently repeated movements were localized along structural trends subparallel to the northwest wall of the New Jersey-New York Triassic half-graben. This correspondence in space is probably not merely coincidental. The fact that large volumes of tholeiitic basaltic magma rose toward the surface in this area during the Late Ordovician (Cortlandt) and again in Late Triassic time suggests some fundamental deep crustal control.

CATACLASTIC DEFORMATION: EVIDENCE FOR REPEATED MOVEMENT

Bayley and others (1914) pointed out the significance of a zone of cataclasite and mylonite in the Hudson Highlands adjacent to the Triassic border fault in New Jersey. Recent investigators have found a zone of brecciated rock approximately 1000 ft wide in gneisses west of the border fault in the vicinity of the Delaware River near Frenchtown, New Jersey (Drake and others, 1961; Drake, 1969). At this locality, either Paleozoic or Triassic rocks are in fault contact with the older gneisses. It was suggested that the intense cataclasis and mylonitization in rocks of the footwall could not have been produced during an episode of Triassic normal faulting, but was caused by either wrench or reverse faulting during a Paleozoic structural event (Drake and others, 1961). These authors thought Triassic faults locally followed the older zones of weakness.

In the Tomkins Cove–Thiells area of New York, near the northern terminus of the Newark basin, both the Paleozoic rocks and the Precambrian gneisses have been extensively mylonitized (Fig. 2). Cataclastic deformation is most pronounced, however, in the gneissic rocks. Here a 200- to 500-ft-wide zone of crushed rock, ranging from cataclasite to ultramylonite, parallels the fault along whose trace Paleozoic and Triassic rocks are downdropped (Fig. 3). As the fault is approached, the Middle Ordovician Annsville Phyllite develops a cataclastic fabric that overprints the regional axial plane foliation. Despite the intense cataclasis in the Paleozoic and Precambrian rocks, exposures of the Triassic fanglomerate within 50 ft of the fault are noncataclastic and are undeformed except for small west-dipping antithetic faults.

The fault contact was exposed briefly during construction at a locality near Tomkins Cove (Fig. 3, Loc. 1). A punky-weathering zone of open-work fault gouge composed of irregularly shaped and oriented fragments of Annsville Phyllite marks the fault contact. Nonfolded but rotated fragments of phyllite 1 to 2 inches in diameter form a loosely compacted porous material. Adjacent outcrops of granite gneiss are mylonitized, containing seams up to several feet thick of jet black well-foliated ultramylonite. Evidence of the extremely severe shearing such as would be required to produce the mylonites and ultramylonites seen in the adjacent granite gneiss is not found at the fault contact.

The nature of the older faulting that produced the mylonite is uncertain. However, displacement of the Paleozoic rocks on the Ramapo fault of Tomkins Cove (Fig. 4) suggests a component of dip-slip movement of 3000 to 4000 ft, judging from the exposures of Poughquag Quartzite on the footwall. A significant component of right-lateral strike-slip movement as shown by the offset exposures of Poughquag Quartzite (Fig. 2), however, cannot be ruled out. Such transverse movement would also be consistent with intense mylonitization of the quartzite that is found on both sides of this fault.

Movement of the Triassic rocks, however, could have been considerably less than the possible 3000 to 4000 ft displacement on the older fault, perhaps as little as 200 to 500 ft of

vertical net slip. It is significant that the Triassic fanglomerate is only in fault contact with the footwall of the main border fault for a distance of 700 ft (Fig. 3). Paleozoic rocks form the hanging wall along most of the fault. Moreover, the strike of the Triassic rocks (Fig. 3) parallels its contact with the older rocks, thus suggesting it is an erosional-depositional contact.

These observations suggest strongly that the cataclastic effects seen in the rocks did not all form at the same time. The final phase of Triassic subsidence probably was responsible

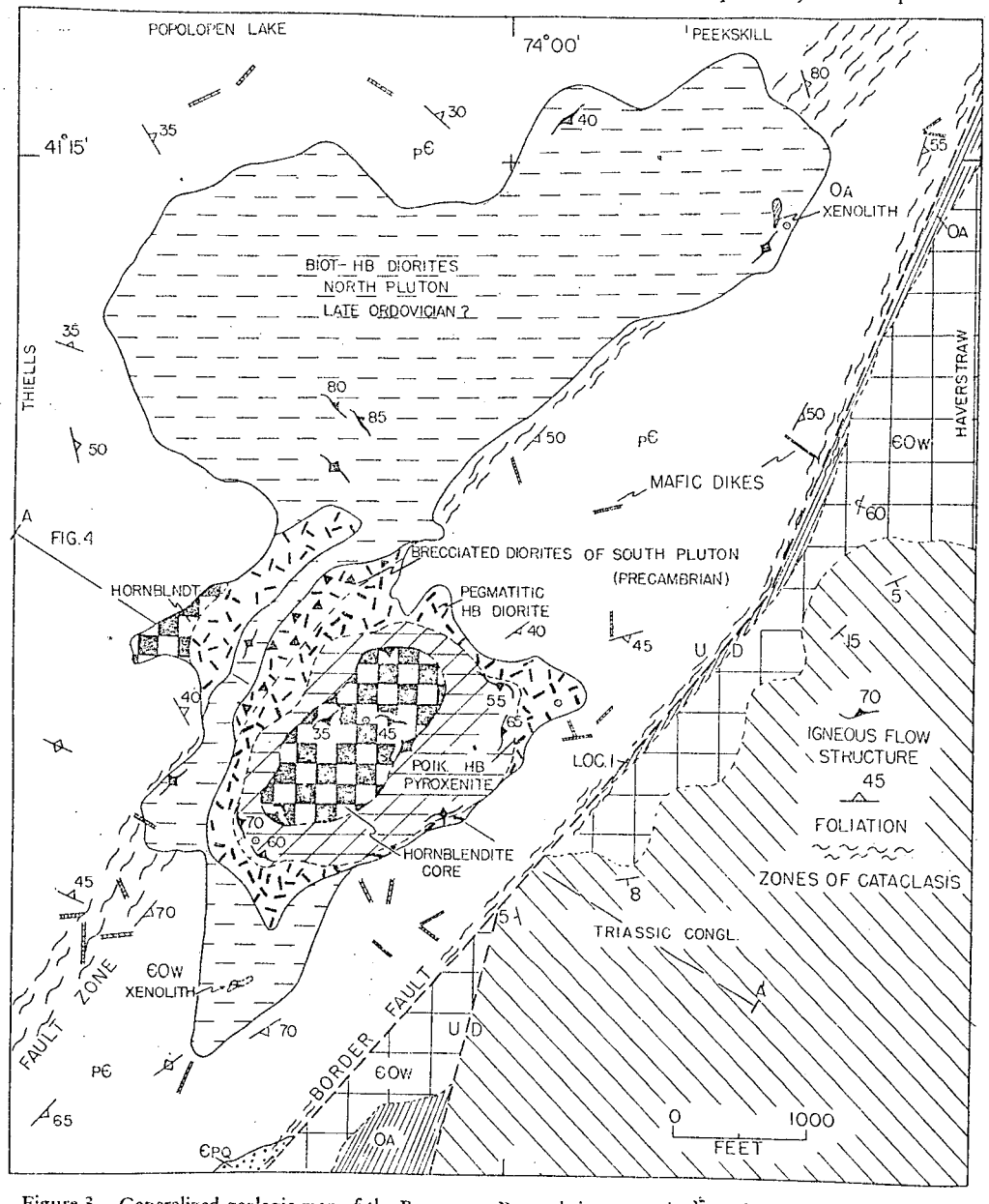


Figure 3. Generalized geologic map of the Ramapo fault at the northern end of the Newark basin near Stony Point, showing the location of the Rosetown pluton and line of section shown on Figure 4. Numbered localities are referred to in text. Explanation: pЄ, Precambrian granite gneiss; ЄpQ, Poughquag Quartzite; ЄOW, Wappinger Limestone; OA, Annsville Phyllite. Igneous units identified on map. Geology mapped by Ratcliffe, 1967-1970; and Shuart, 1968-69.

for the open-work breccia described above. Such an interpretation is consistent with the observation that the Triassic rocks adjacent to the Ramapo fault are not cataclastically deformed. The Triassic fanglomerate unconformably overlies the Wappinger Limestone in this area and, judging from surface dips, the bottom of the Triassic basin is only several hundred feet beneath the surface at the border fault (Fig. 4). Because no significant Triassic downdropping can be proved at the northern end of the Newark basin, it appears unlikely that the Triassic sediments ever extended much farther northeast than the present exposures of the Triassic unconformity, thus eliminating the necessity of the Danbury anticline of Sanders (1963, p. 510).

Extensive mylonitization along a complex fracture zone is found along the extension of the Ramapo fault east of the Hudson River at Annsville and Canopus Hollow. It is significant that cataclastic deformation similar to that ascribed to the older faulting at Tomkins Cove marks the extension of the fault zone to the northeast rather than the open work breccia of the youngest fault episode. Cataclastic deformation took place at various times in the Canopus area, judging from the cross-cutting relationships of mylonite zones. However, the details are imperfectly known at present. The field relationships as presently understood are presented in Figure 5. The area was mapped by the writer at a scale of 1 in.: 1000 ft during investigation which spanned a three-week period. The geologic relationships vary significantly from previous studies by Berkey and Rice (1919) and Ohan (1964).

The mylonite zones shown on Figure 5 are all marked by strong development of minor folds showing right-lateral shear senses and near vertical fold axes. Evidence for right-lateral transcurrent faulting is best displayed along the western side of the Canopus Valley marble belt in the vicinity of the Canopus pluton. Here, offset of a distinctive 1.5- to 3-ft-thick magnetite deposit, shown by a special symbol on the map (Fig. 5, Loc. 2), suggests a right-lateral displacement of 4 km (2.48 mi). The age relationships of this fracturing will be discussed in the section dealing with the intrusive rocks.

THE MIDDLE ORDOVICIAN UNCONFORMITY: EVIDENCE OF LOCAL UPLIFT

Bucher (1957) reported the remarkable exposures at a road cut on Route 9 near the town of Annsville, New York, on the east side of the Hudson Valley just north of Peekskill (Fig. 5, Loc. 1). At this locality, a limestone containing subrounded as well as angular clasts of Precambrian gneiss, quartzite, and dolostone rests unconformably on gneisses of the Hudson Highlands. The limestone matrix was reported to contain "cystid" fragments (Bucher, 1957, p. 669), and on the basis of correlation with a similar fossiliferous rock that overlies the Wappinger Limestone at Tomkins Cove (Bucher, 1957) was assigned a Middle Ordovician age. Bucher's suggestion that this limestone represents the base of the regionally recognized Middle Ordovician unconformity is generally accepted (Ratcliffe and Knowles, 1969).

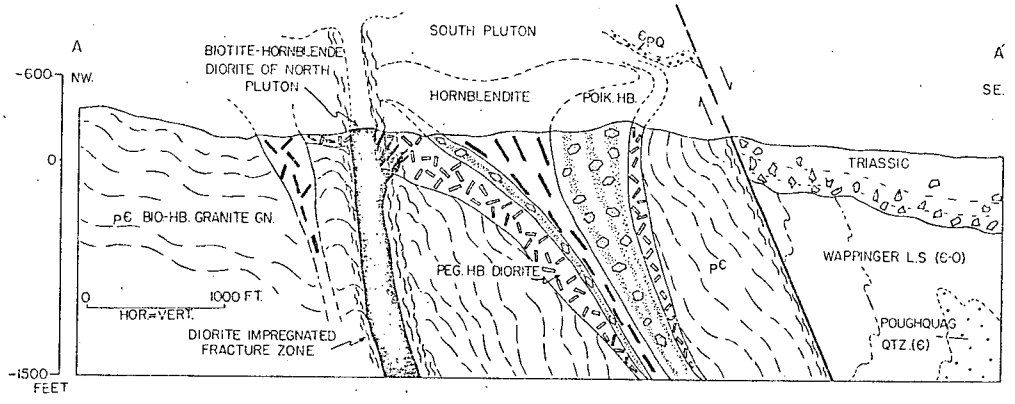


Figure 4. Profile and section of the Ramapo fault in the vicinity of the Rosetown pluton, showing the offset of the Paleozoic rocks and the Late Ordovician fault zone into which diorites of the younger part of the Rosetown pluton intrude. See Figure 3 for line of section.

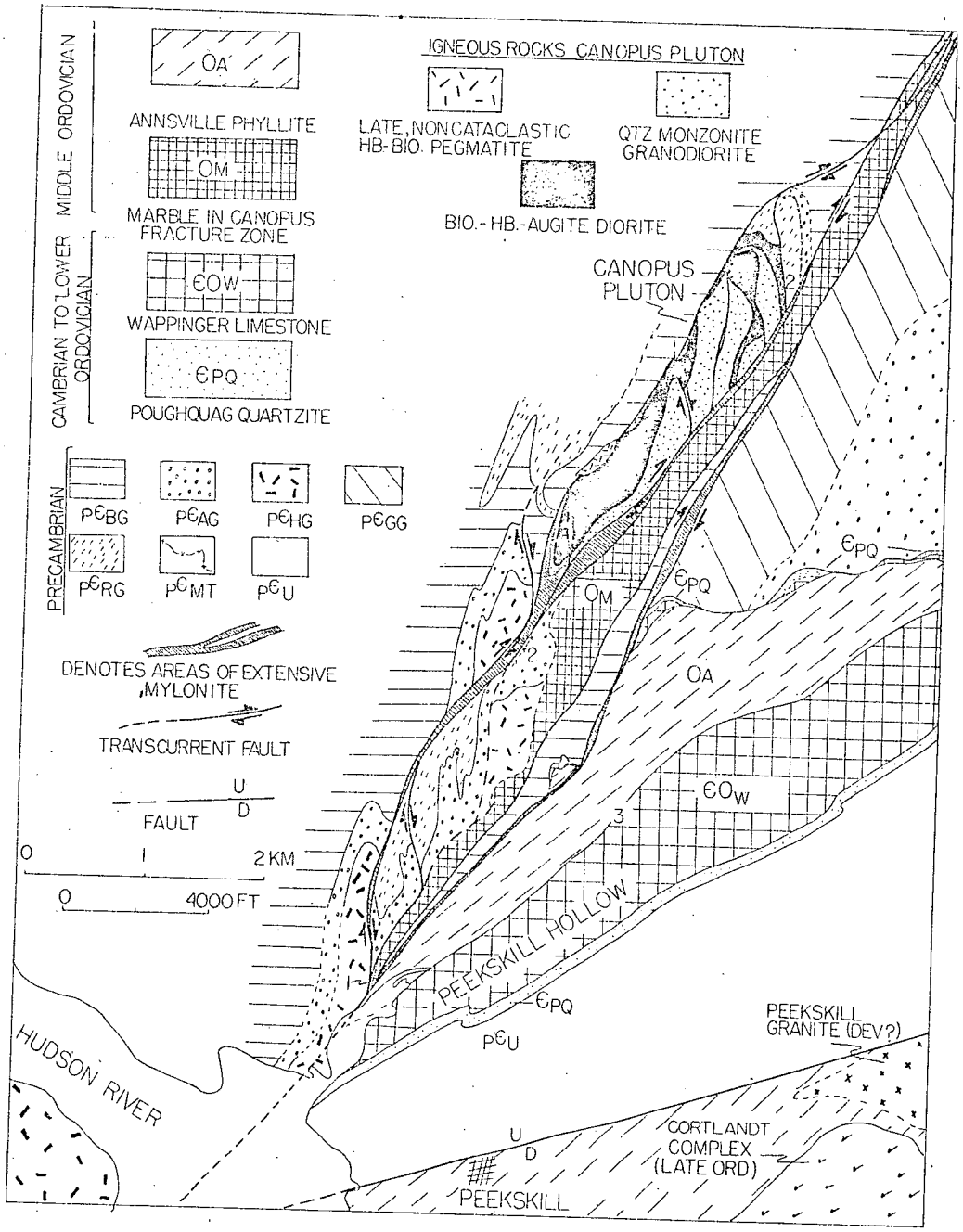


Figure 5. Geologic map showing the projection of the Ramapo fault system northeast of the Hudson River along the Canopus Valley (Peekskill quadrangle, New York), and the position of the Canopus pluton. Subdivisions in the Precambrian: pЄBG, biotite-plagioclase-quartz paragneiss; pЄAG, amphibolitic gneiss; pЄHG, hornblende-biotite granite gneiss; pЄGG, granodioritic gneiss; pЄRG, rusty-weathering fine-grained biotite granite gneiss; pЄMT, magnetite ore and associated calc silicates; pЄU, undifferentiated gneisses. Index to locations: (1) unconformity at Annsville, (2) offset magnetite deposits, (3) Annsville contact at Peekskill Hollow.

The Route 9 exposure is located at the southwestern end of a long narrow inlier of carbonate rocks in the Canopus Valley that lies along the northeastern projection of the Ramapo fault from the Tomkins Cove area.

The carbonate rocks of Canopus Valley were assigned a "Trentonian" age by Bucher (1957) on the basis of the reported fossils at Annsville, and that interpretation is used in Figure 5. However, study of the carbonate rocks by the author suggests that this interpretation may be too simple, as some of the dolomitic rocks within the valley that appear to be more recrystallized than the limestone at Annsville may eventually prove to be lower Paleozoic Wappinger equivalents or even late Precambrian in age as suggested by Berkey and Rice (1919, p. 105–106). This problem is unresolved at present.

The Cambro-Ordovician sequence is well preserved in a syncline (Bucher, 1957, p. 669) in the adjacent Peekskill Hollow (Fig. 5). The fossiliferous base of the Annsville Phyllite (Ratcliffe and Knowles, 1969, p. 50) rests on Wappinger Limestone approximately 1200 ft above the Precambrian basement on the eastern side of the syncline (Fig. 5, Loc. 3). The contact of the Annsville on the western limb of the syncline unconformably rests on Wappinger Limestone, Poughquag Quartzite, or Precambrian gneiss (Fig. 5). Thus the pre-Middle Ordovician erosion can be shown to have cut most deeply in the direction of the unconformity at Annsville. Local differential uplift in excess of 1200 ft is suggested. Bucher (1957, p. 669) suggested that warping was responsible for the truncation. However, the development of coarse clastic debris (clasts as much as 1 ft in diameter; Bucher, 1957, p. 668) calls for considerable local topographic relief such as could be accomplished in a block-faulted, shallow-water marine environment.

Study of the matrix of the "Trenton" limestone is particularly interesting. Both at the Canopus locality (Fig. 2, Loc. 1) and at Tomkins Cove (Fig. 2, Loc. 2) the limestone is marked by distinctive beds 1/4 to 1/2 in. thick, rich in sand-sized silicate detrital debris including quartz grains and some rock fragments of gneiss, calc-silicate rock, and detrital feldspar (Bucher, 1957, p. 668; Ratcliffe, unpub. data). It is significant that this detrital debris is absent in the same basal limestone exposed at Verplanck Point (Fig. 2, Loc. 3), Peekskill Hollow (Fig. 2, Loc. 5), and south of the Cortlandt Complex at Crugers (Fig. 2, Loc. 4) (Ratcliffe and Knowles, 1969). The change in the basal limestone facies in a northwest direction as the Ramapo fault is approached (at the latitude of Tomkins Cove) suggests that an uplifted area existed in that direction during Middle Ordovician time. This evidence and the observable unconformity at Annsville suggest that block faulting may have been active on the Ramapo fracture system in pre-Middle Ordovician time.

Block faulting of this kind is believed to have been important during the formation of the Middle Ordovician unconformity in the Middlebury synclinorium and its southern extension in western New England (Zen, 1968). A locality in the Pawlet quadrangle, Vermont, described by Thompson (Thompson and Shumaker, 1967, p. 87–89), is sufficiently similar to the relationships thought to exist at Peekskill to warrant discussion here. On the north slopes of Dorset Mountain, Vermont, the Middle Ordovician Ira Formation unconformably overlies adjacent outcrops of Precambrian Mount Holly Gneiss and Lower Ordovician Shelburne Marble. Because the Ira shows no signs of having been offset itself, and because the unconformity surface overlaps rocks as young as the Bascom Formation locally, a post-Lower Ordovician–pre-Ira normal fault was proposed to account for the field relationships. Locally in the vicinity of the fault, volcanic rocks, the Baker Brook volcanics, form a unit immediately above the unconformity. Evidently the pre-Ira Tinmouth Disturbance, as it is locally known in Vermont (Thompson and Shumaker, 1967, p. 88), involved block faulting as well as volcanic activity that presumably reached the surface via the pre-Ira faults.

The Peekskill locality and the nearby Rosetown area also underwent block faulting, erosion, and basaltic magmatism (in the form of dikes and small plutons), suggesting crustal instability similar to that active in New England at the same time.

IGNEOUS INTRUSIVES IN FAULT ZONES: RELATIONSHIP TO REGIONAL FAULTS

Igneous rocks of the Cortlandt Complex and other mafic rocks are extensively developed to the east of the Ramapo fault (less than 1 mi east) and along a fault that extends northeast from Peekskill, forming the southeastern boundary of the Hudson Highlands against the Manhattan Prong (Fig. 1). Only rarely, how-

ever, are these mafic rocks intrusive into the Highlands block. The Rosetown pluton (Kemp, 1888; Shuart, 1969; Ratcliffe and Shuart, 1970) several hundred feet west of the Ramapo fault at Tomkins Cove (Fig. 1, Loc. 4) and a small biotite diorite-monzonite complex (Fig. 1, Loc. 3; Fig. 5) along the west wall of the Canopus inlier are the exceptions.

Both the Canopus and Rosetown localities are located along the trend of the Ramapo fault and have textures and structural relationships indicating that they were intruded during a tectonic episode of brittle fracturing of the basement rocks along the Ramapo fault trend. Although these plutons were attributed to Cortlandt magmatism (Fisher and others, 1962; Isachsen, 1964, Fig. 5), the evidence presented here and elsewhere (Ratcliffe and Shuart, 1970; Ratcliffe and R. G. Senechal, in prep.) suggests that the igneous rocks are in part Precambrian and in part lower Paleozoic in age.

The Rosetown pluton (mapped in detail by Shuart, 1969) has long been regarded as a westward extension of the Cortlandt Complex (Kemp, 1888). The Rosetown (Fig. 3) is an elongate intrusive, the long axis of which trends N. 40° E., roughly parallel to the Ramapo border fault that lies immediately east of it. The pluton actually is composite, having an older funnel-shaped mass of hornblendite and hornblende diorite in the southeast (Shuart, 1969; Ratcliffe and Shuart, 1970).

This older pluton and the surrounding Precambrian gneisses have been fractured along a shear zone that trends N. 40° E., coplanar with the nearby Ramapo border fault at Tomkins Cove. The fracture zone, cutting the older part of the pluton, coincides with the northerly projection of the Ramapo fault from a point 5 mi north of the New Jersey–New York state line (Fig. 1). This fracture zone separates blocks of Precambrian hornblende and biotite granite gneiss having different foliation trends. Foliation in the gneiss of the eastern block trends N. 40° E. parallel to Paleozoic structures in the adjacent Manhattan Prong, a direction nearly at right angles to the strong northwest trends in the western block (Fig. 3). Dioritic magma that formed the younger and major part of the Rosetown pluton (Figs. 3 and 4) rose to the surface along this fracture (Ratcliffe and Shuart, 1970). Blocks of Precambrian gneiss, rocks of the older pluton, Wappinger Limestone, and Annsville Phyllite are found as xenoliths, thus requiring a post-Middle Ordovician age for the diorite (Kemp, 1888; Frimpter, 1967; Ratcliffe and Shuart, 1970). North and south of the pluton, unsheared lamprophyric dikes (largely spessartites) and small pods of diorite intrude the shear zone. These lamprophyric dikes intrude gneissic rocks in the vicinity of the Ramapo fault near Tomkins Cove (Fig. 3) and, although foliated near the fault, have not been as intensely deformed as the mylonitized country rocks.

Igneous rocks from the younger part of the Rosetown pluton include biotite-hornblende diorites, lamprophyres, and cortlandtite that match in detail lithic types found in the Cortlandt intrusions at nearby Stony Point, where the Wappinger-Annsville (Inwood-Manhattan A) have been intruded (Ratcliffe, 1968b). The proximity of these two intrusives (Fig. 2), their maximum age, and the similarity of igneous rock types may indicate that they are approximately coeval. Based on a biotite K-Ar age determination from norite of the main body east of the Hudson River, the Cortlandt Complex is thought to be of Late Ordovician-Early Silurian age (Long and Kulp, 1962). Because the Cortlandt Complex is recognized to cut fossiliferous rocks of probable Middle Ordovician age (Ratcliffe and Knowles, 1969, p. 53), the biotite age cited above is regarded as reliable.

Igneous flow-oriented hornblende from the south pluton at Rosetown yielded a K-Ar age of 810 ± 8 m.y., suggesting that the older part of the pluton was Precambrian (Ratcliffe and Shuart, 1970). Subsequent isotopic studies (Ratcliffe and R. G. Senechal, in prep.), however, suggest that the hornblende ages may be excessively old, because hornblende from the diorite that includes a xenolith of Annsville Phyllite (Middle Ordovician) yielded an anomalous 580 ± 20 m.y. K-Ar age. Although the data are not complete yet, these preliminary results suggest that the older part of the Rosetown may not be as old as the 810-m.y. age reported by Ratcliffe and Shuart (1970). It should be noted that because of the lack of fossils in the Annsville xenolith, the geologic relationships are not firm enough to prove that the hornblende ages are erroneous. Unlike the diorites within the fracture zone, the rocks of the southern intrusive center do not contain xenoliths of Paleozoic rocks and yield old isotopic ages, thus suggesting a Precambrian age. The age of the fracturing related to the intrusion of the northern diorites that are typical Cortlandt rocks on geologic

grounds is expected to be post-Middle Ordovician, a time consistent with the suspected Late Ordovician–Early Silurian age of the main mass of the Cortlandt.

This argument and the observation that the younger diorites have been intruded into an openwork fracture system suggest that normal faulting was active here in Late Ordovician–Early Silurian time (Ratcliffe and Shuart, 1970). The parallelism of this fracture zone with the Ramapo fault indicates that a deep-seated fracture system was active here in the lower Paleozoic, presumably at a time postdating the uplift that produced the unconformity at Canopus Hollow.

In the Popolopen Lake area northwest of the Rosetown Complex, Dodd (1965) mapped a series of north- to northeast-trending faults (Fig. 2). On the basis of the comparative stratigraphy in different blocks, he proposed a normal-fault component for most of these and assigned them a Triassic age. However, abundant lamprophyric dikes, compositionally and geographically closely tied to the diorites of the Rosetown pluton, fill northeast-trending fractures in the gneiss. Characteristically, these dikes postdate the northeast-trending faults (Dodd, 1965). If the dikes are Rosetown-Cortlandt equivalents, as the field and petrographic data suggest (Ratcliffe, 1968b; Shuart, 1969), this faulting may also have been of Ordovician or older age. Thus, intrusive relationships of the diorite cited above and the lamprophyres indicate an age older than Triassic for some of the northeast-trending faults. Triassic reactivation of older faults, however, cannot be ruled out for some of the faults shown on Figure 2, so that Dodd's age assignment may in part be correct.

Perhaps these faults, too, have undergone repeated movement during a long period of time. The Timp Pass fault (Fig. 2), for example, is thought to be a Precambrian reverse fault at its northern end (Lowe, 1950) but a Triassic normal fault along its southern trace (Dodd, 1965). Both authors could be correct if the fault were reactivated as a hinged fault showing increasing net slip to the southwest, a mechanism proposed for the Ramapo fault itself (*see* Van Houten, 1969, Fig. 11). Rejuvenation of old northeast-trending faults during the Triassic has also been suggested by Offield (1967, p. 67–69) for the Goshen-Greenwood Lake area of the Hudson Highlands (Fig. 1, Loc. 9).

Igneous rocks similar to those of the Rosetown pluton crop out along the fracture zone on the west side of the Canopus Valley in the Peekskill 7-1/2 min. quadrangle (Fig. 4). The Canopus pluton has intrusive relationships locally with the bordering Precambrian gneisses. However, the eastern and western contacts of the igneous rocks are extensively mylonitized and faulted along N. 30° to N. 40° right-lateral transcurrent faults. The igneous rocks of the Canopus pluton were interpreted by Fisher and others (1962) as Cortlandt equivalents. However, the Canopus pluton contains felsic rocks, monzonites, quartz monzonites, and granodiorites that are rare or absent in the Rosetown pluton. Moreover, biotite separated from the Canopus diorite yielded a K-Ar minimum age of 700 ± 28 m.y. (Ratcliffe and R. G. Senechal, in prep.). Steeply plunging flow structures present in the igneous rocks and the filling of subsidiary right-lateral shears by late stage differentiates suggest that right-lateral strike-slip faulting was active at the time of the intrusion in late Precambrian time. Thus, some of the fracturing along the west side of Canopus Hollow may be late Precambrian in age.

The marble of the Canopus Valley is thought to be "Trentonian" in age on the basis of crinoid remains reported by Bucher (1957) from a road cut on Route 9 (Fig. 5, Loc. 1). The recrystallization and mylonitization of this marble in the Canopus Valley may have been the result of intense shearing within the fault zone during a second period of transcurrent faulting that was accompained by intrusion of mafic and pegmatitic dikes noted by Berkey (1907, p. 369) and Ohan (1964). Locally the mafic dikes are boudinaged and brecciated in areas where the marble is cataclastically deformed (Ohan, 1964).

Faulting and cataclasis of the Annsville-Wappinger sequence on the eastern side of the valley along the projection of the Ramapo fault from the Tomkins Cove area indicate post-Ordovician fracturing. Although this fault has been interpreted as a normal fault (Berkey and Rice, 1919), the intense cataclasis and the strong development of right-lateral minor folds having steeply plunging axes suggest transcurrent faulting. The offset of the Annsville Phyllite in a left-lateral sense shown on the map does not agree with the fabric within the mylonite zone; thus this offset is probably apparent. The age of post-Precambrian faulting, accompanied by extensive mylonitization and right-lateral movement, can only be dated by the observa-

tion that pegmatitic dikes in the mylonite zones and in the marble of the Canopus belt have not been deformed (Ohan, 1964). The youngest "granitic" rock recognized in this area is the Peekskill Granite, which suggests that even the late fracturing was pre-Peekskill. The age of the Peekskill Granite is not known with certainty, although concordant K-Ar and Rb-Sr muscovite ages of 355 ± 15 m.y. (Long and Kulp, 1962) indicate a Devonian or older age. Xenoliths of Manhattan Schist and Cortlandt ultramafic rocks in the Peekskill reported by Espeho and Mattson (1970) indicate that the granite is probably not older than Late Ordovician Early Silurian.

This line of reasoning points to a Precambrian to Early Paleozoic age for the important fracturing in the Canopus Valley similar to that adduced for the Rosetown area. The evidence presented in these first three sections argues strongly for repeated pre-Triassic fault movements in N. 30° to 40° E. trends at the north end of the Ramapo fault in the late Precambrian, the Early Ordovician, and again in the Late Ordovician.

REPEATED FAULTING DURING LATE TRIASSIC TIME: THE BORDER CONGLOMERATES

Coarse Triassic border conglomerates locally flank the northwest edge of the Newark Basin and belong to the Hammer Creek Formation (Glaesser, 1966; Van Houten, 1969). Clasts of Cambro-Ordovician dolostones and quartzites, Siluro-Devonian rocks, and locally Precambrian gneisses make up the bulk of the clasts in these deposits (Savage, 1968; Van Houten, 1969). The distribution and composition of these fanglomerates indicate local derivation from the uplifted Paleozoic cover of the Hudson Highlands (Carlston, 1946). The high relief necessary to form such conglomerates suggests repeated uplift of the Highlands, whereas the change in the character of the deposits from place to place may indicate differential uplift. In post-Brunswick time, faulting downdropped the Triassic rocks along the present border fault.

Near Stony Point, the Hammer Creek Formation evidently rests unconformably on the Paleozoic rocks (Inwood and Manhattan Schist) (Ratcliffe, 1968a, p. 200), thus exposing the floor of the Triassic basin. The post-Brunswick faulting need not have produced large displacements of the Triassic at the border fault near Tomkins Cove for the reasons previously mentioned. This implies that the Ramapo fault is hinged at a point north of Tomkins Cove with increasingly greater net slip to the southwest (*see* Van Houten, 1969, Fig. 11). Likewise, the lack of cataclasis in the Triassic rocks bordering the Ramapo fault (Fig. 3) and the severe mylonitization in the footwall block suggest that post-Brunswick movement was rather slight.

The abundant igneous activity in the Newark Basin indicates the presence of a deep crustal fracture zone beneath the point where the igneous rocks were intruded or where they reached the surface. The relationship of the large intrusive Palisades phase to the east and the Watchung flows to the west of the basin suggests that the border fault at depth served as an avenue of magma ascent, although magma apparently never reached the surface along this fault.

RECENT SEISMIC ACTIVITY

Page and others (1968) recently presented evidence of seismic activity near the Ramapo fault. Four earthquake epicenters recorded since 1962 have been located on the southeastern side of the fault from Peekskill south to Pompton Lakes. Richter values reported fell in the 1.0 to 2.0 range. Although accurate hypocenter determinations were not available, it was reported that the four earthquakes could have originated at moderate depths (5 to 10 km) on a southeast-dipping fault whose trace could be consistent with that of the Ramapo fault. Page and others (1968) suggest that fault movements are taking place at the present time along this old fracture, but they could not judge whether the crustal adjustments were in response to tectonic stresses or were the result of unloading of glacial ice. In the light of the long history of faulting in this area, from the late Precambrian to the Triassic, it may be reasonable to suggest that these recent movements are also of tectonic origin.

Minor seismic activity has recently been recorded for the Lake Hopatcong area of northern New Jersey (Fig. 1, Loc. 8) located in the Dover and Stanhope quadrangles, 13 mi northwest of the Ramapo fault (Sbar and others, 1970). The earthquake activity is interpreted to have taken place along the inferred southwest extension of a N. 40° E.-trending normal fault that forms the northwest side of a graben that downdrops Devonian rocks (Buddington and Baker, 1961). Offield (1967, p. 67–68) suggested that this fault in New York State was an Ordovician reverse fault rejuvenated as a

Triassic normal fault. A first motion study of the earthquakes indicates normal faulting for the Lake Hopatcong tremors, and Sbar and others (1970) suggest that this may be a case of reactivation of a Triassic fault.

RELATIONSHIP OF FAULT ACTIVITY TO THE PROPOSED READING PRONG ALLOCHTHON

The arguments for the tectonic longevity of the Ramapo fracture system presented here have an important bearing on a major unresolved tectonic problem in the Hudson Highlands. Isachsen (1964) suggested that the entire Reading Prong was a large allochthon emplaced in pre-Cortlandt time (Late Ordovician–Early Silurian) from a more southeasterly source. The pre-Cortlandt age was required by the fact that rocks of the Rosetown pluton attributed to the Cortlandt Complex intrude the supposed allochthon (Isachsen, 1964, p. 825) and autochthon. The radiometric and geologic investigations cited here and in recent work (Shuart, 1969; Ratcliffe and Shuart, 1970; Ratcliffe and R. G. Senechal, in prep.) equate some of the Rosetown rocks with the Cortlandt and thus support in part Isachsen's interpretation regarding timing of the possible movement. However, the Precambrian age of igneous activity at Canopus and of the older part of the Rosetown pluton is not in agreement with Isachsen's (1964) age assignment.

The idea of strong westward movement of Precambrian massifs in western New England and the Reading Prong has gained support from recent studies. In the Berkshire Massif of western Massachusetts (S. A. Norton, 1969; Ratcliffe, 1969) strong remobilization of the gneissic basement took place in the middle Paleozoic under metamorphic conditions ranging from sillimanite to garnet grade. Large-scale nappes having Precambrian cores and involving rocks as young as Middle Ordovician show surface displacement westward of at least 4 mi and perhaps as much as 8 mi (Ratcliffe, 1969; Ratcliffe and D. S. Harwood, unpub. data). The Berkshire Massif is regarded by the author as parautochthonous in the sense that it is only partially detached and traceable to a root zone along its eastern edge (for a discussion of the terms parautochthonous and allochthonous nappes, *see* Hills, 1963, p. 250).

The detailed work of Drake (1969) and his co-workers in the Pennsylvania part of the Reading Prong indicates that rocks as young as the Middle Ordovician Martinsburg Formation have been overturned and moved westward as the cover of a large nappe cored with Precambrian gneiss. Both Isachsen (1964) and Drake (1969) favor the interpretation of an entirely rootless (allochthonous) Reading Prong. Workers such as Offield (1967, p. 68–70) and Smith (1969, p. 44–45) believe that the overthrusting is quite limited along the western edge of the Reading Prong in New York and adjacent New Jersey. Thus the parautochthonous or allochthonous nature of the Reading Prong is disputed at the present time.

The structural arguments presented here and by Ratcliffe and Shuart (1970) suggest that the Ramapo fracture system has been operative in the rocks of the Hudson Highlands since late Precambrian time. Movement in pre-Middle Ordovician time is dated by the Middle Ordovician unconformity at Annsville. Facies in the limestone at the base of the Manhattan Formation or Annsville Phyllite are not offset by the supposed trailing edge of the proposed allochthon. Moreover, detrital debris in the rocks above the Middle Ordovician unconformity coarsens and becomes more abundant as the Ramapo fault is approached, which indicates uplift at the site of the present Highlands block in pre-Middle Ordovician time. This evidence suggests strongly that the southern edge of the Hudson Highlands could not have been emplaced in Late Ordovician time as proposed by Isachsen (1964).

A stratigraphic argument based on a regional study of the Lower Cambrian quartzite sequence seems pertinent here. Within the Reading Prong, the Lower Cambrian strata, having sedimentary (unconformable) contacts with the Precambrian rocks, are predominantly quartz-rich facies variously known as the Hardyston or Poughquag Quartzite. Locally silica- or hematite-cemented conglomerates form the base of the formation (Aaron, 1969; Balk, 1936; Ohan, 1964; Ratcliffe, unpub. data). This quartz-rich lithology is common in the western outcrop belts of the Cheshire or Poughquag quartzites in eastern New York and western Massachusetts. More easterly exposures of these formations or their equivalents, the Dalton and Hoosac Formations (in western Massachusetts and Connecticut) (S. A. Norton, 1969; Ratcliffe, 1969) and the Lowerre Quartzite–in most of the Manhattan Prong–(M. F. Norton, 1959; Hall, 1968), differ markedly from this western facies. In the cen-

tral and eastern part of the Manhattan Prong, feldspar-rich granulites, micaceous feldspathic quartzites, and quartz-rich schistose rocks lithically similar to the Dalton Formation of western Massachusetts represent the bulk of the lower Cambrian clastic sequence (Leo Hall, 1970, personal commun.; Ratcliffe, unpub. data). The lack of the distinctive eastern sedimentary facies (Dalton-Hoosac) in the Reading Prong suggests strongly that its northern end is not allochthonous, because the eastern impure facies of the quartzite sequence, the Lowerre, crops out in the area of the proposed root zone.

Thus the structural and stratigraphic arguments presented here suggest strongly that the Hudson Highlands is rooted along its southeastern edge in New York State. However, this interpretation does not necessarily require that the southern or western edge of the Reading Prong be rooted as well. A half klippe would equally well explain the geologic relationships seen at the southern end of the Reading Prong (Smith, 1969, p. 45), whereas a parautochthonous style of the Hudson Highlands, similar to that proposed here for the Berkshire Massif, would satisfy some of the data in New York State.

DISCUSSION

Many different lines of evidence indicate that protracted faulting took place in the vicinity of the northwest border of the Newark basin from the late Precambrian to the Triassic and perhaps is continuing at present. Although it is not suggested that all movements were in response to the same tectonic forces, the detailed analysis of the several localities discussed points to repeated movement along a N. 30° to 40° E.-trending fracture system of regional importance. Right-lateral transcurrent faulting not previously recognized seems to have been of particular importance. Some fundamental crustal feature or structural grain predetermined the later movements. The geologic record is not clear in this regard, but perhaps the original grain that developed in Precambrian time is part of a major crustal fracture zone separating plates of lithosphere. Nevertheless, this interesting geologic feature has experienced a long tectonic life. Some mechanism allowing localization of tectonic activity has been operative here over a long period, a process sometimes referred to as tectonic heredity.

A 280-m.y. period of intermittent fault movement and igneous activity is indicated for the Ramapo fault system, spanning the time from the initial pre-Trenton disturbance to post-Brunswick Late Triassic faulting. If the fracturing along the west side of the Canopus Valley is considered part of the same fracture system, as seems likely, activity in this zone may have extended back into the Precambrian. Although no field data indicate that any post-Mesozoic faulting took place, the seismic activity recently recorded by Page and others (1968) suggests reactivation is currently underway and extends the possible tectonic life span to 600 or 700 m.y.

In addition to its remarkable longevity, the Ramapo fault system also marks the boundary between structurally different terranes, separating the Reading Prong from both the Newark basin and the rocks of the Manhattan Prong. This fracture system is known to have had deep crustal connections that allowed intrusion of basaltic magmas in late Precambrian, Ordovician, and again in Late Triassic time. All the evidence suggests that the Ramapo fault system and the Newark basin border fault in general may be part of a fundamental crustal fracture zone such as the North Pyrenean fault-zone of southwestern France (de Sitter, 1959, p. 175–176).

A commonly raised and legitimate objection to the idea of old linear faults in orogenic belts is the lack of subsequent deformation. That is, why are the fault surfaces not folded? The answer may lie in the fact that the later regional structural grain is nearly colinear with the older faults. Therefore, the steeply dipping fault surfaces are not likely to reflect the effects of later folding. Subsequent tectonic stresses may have been taken up on these faults and thus would reinforce the difference in structural style between terranes adjacent to such a fault. This interpretation seems likely in light of the evidence of significant right-lateral transcurrent faulting along the fracture system at Canopus Hollow. This probably is the case at the boundary between the Reading and Manhattan Prongs in the vicinity of the Ramapo fault. The effects of multiple Paleozoic metamorphism and structural deformation so clear in the Manhattan Prong adjacent to the border fault (Ratcliffe, 1968a, 1968b) and elsewhere in the Manhattan Prong (Hall, 1968; Langer and Bowes, 1969; Bowes and Langer, 1969) are difficult to detect in the Precambrian rocks of the Hudson Highlands west of the Hudson River (Lowe, 1950; Dodd, 1965; Dallmeyer,

1969). Evidently, Paleozoic structural overprinting has been slight in rocks west of the Ramapo fault.

The acceptance of this explanation for the Ramapo fault system calls for a degree of tectonic permanence not commonly dealt with in current global tectonic models. It seems that the faults that produced the Newark basin in Late Triassic time were not initiated by Mesozoic tectonics alone, as proposed by Van Houten (1969, p. 330), but rather were merely reactivated at that time. The initial formation of this fracture system evidently extends at least as far back into geologic past as the Middle Ordovician, and probably back to the Precambrian.

The role that the Ramapo fracture system played in Taconic and later orogenesis is unknown at present, but it seems certain that it was a major zone of crustal weakness and movement during the formation of the Appalachian orogen. Such major tectonic features as the bend in the trend of the Appalachian Mountain belt at the Hudson River, the extent of the Taconic orthotectonic belt, and the westward limits of Acadian reheating may somehow be related to this fault system.

The detailed movements on the Ramapo fracture system are imperfectly understood at present. However, the geologic relationships described here suggest the following tectonic history: (1) late Precambrian, right-lateral faulting concomitant with intrusion of the Canopus pluton, followed by post-tectonic intrusion of the older part of the Rosetown pluton; (2) Early Ordovician block faulting with oceanward block moved down, erosion on the western block, producing the Middle Ordovician unconformity at Annsville; (3) renewed normal(?) faulting in Rosetown area and intrusion of diorites of younger part of the Rosetown pluton in the Middle to Late Ordovician; (4) intense right-lateral transcurrent faulting in post-Middle Ordovician to pre-Middle Devonian time, producing cataclasis of Precambrian to Middle Ordovician rocks along fracture zone. This movement may have been in part synchronous with Taconic deformation and metamorphism in the adjacent Manhattan Prong; (5) Late Triassic rejuvenation of the old fracture system as a system of hinged normal faults, producing the Newark depositional basin. Block faulting continued during the Late Triassic and possibly into the Jurassic.

Except for the suspected late Precambrian right-lateral movement, the movements described here are broadly consonant with the plate-tectonic model for the origin of the northern Appalachians proposed by Bird and Dewey (1970). According to their scheme, the northern Appalachians formed as a result of late Precambrian to Ordovician expansion and Ordovician to Devonian contraction of the proto-Atlantic ocean basin. Items (2) and (3) above could have formed during the extensional phase, and (4) during the contractional phase. Perhaps the intense right-lateral deformation on the Ramapo fracture system (phase 4) is related to the disappearance of the old proto-Atlantic ocean rise beneath the eastern edge of the North American continent (Bird and Dewey, 1970, Fig. 9) in much the same way that the San Andreas fracture may be related to the present position of the East Pacific rise.

The answers to these and other questions must await the results of detailed field and isotopic investigations. Although the interpretations in this paper are necessarily speculative, the writer hopes that the ideas presented will suggest fruitful areas of investigation to other field geologists.

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