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# ISOTOPIC AGE STUDY OF METAMORPHISM AND INTRUSION IN WESTERN CONNECTICUT AND SOUTHEASTERN NEW YORK†

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ABSTRACT. K-Ar and Rb-Sr ages for a variety of metamorphic and igneous rock types in southeastern New York and western Connecticut are reported. K-Ar ages range from 480 m.y. to 240 m.y. The data suggest that at least three metamorphic events affected the region. The earlier metamorphism probably occurred 460 to 480 m.y. ago; the second, about 360 m.y. ago; and the third and latest event, about 255 m.y. ago. These ages correspond to the Taconic, Acadian, and Alleghanian orogenies. Ages reported in the literature on undeformed pegmatites and data from the present study on undeformed intrusive bodies support this conclusion, although data concerning the 255 m.y. event are not so conclusive. Rb-Sr whole-rock data on the Waterbury formation give an isochron age of 465±50 m.y. Although the data do not preclude a Precambrian age for the Waterbury gneiss dome, evidence to suggest a Grenville-type age is absent.

## INTRODUCTION

Several systematic age studies have been made on the igneous and metamorphic rocks of the Appalachian region using isotopic dating methods.

The stratigraphic interpretation and correlation in much of the region has been complicated by a number of periods of metamorphism and intrusion. The isotopic investigations have contributed greatly to geological interpretation of the timing of these events. As a result, a number of periods of igneous activity have been defined, which, together with metamorphic age patterns, indicate maximum activity in the Paleozoic at 460, 400, 360, and 250 m.y. ago, and in the Mesozoic at 180 m.y. ago. Rodgers (1967) has recently compiled geological information on the orogenic movements in the Appalachian region.

The age studies include the work of Tilton and others (1958), Wasserburg, Pettijohn, and Lipson (1957), Long, Kulp, and Eckelmann (1959), Kulp and Eckelmann (1961), Lapham and Bassett (1964), and Wetherill and others (1965, 1966) in the southern Appalachians. Results of investigations in northern New Jersey and southeastern New York have been published by Long and Kulp (1958, 1962), Long, Cobb, and Kulp (1959), and Long (1962). For the Northern Appalachians, the results of several investigations have been published and summarized. These include Faul and others (1963), Hurley and others (1960), Poole, Kelley, and Neale (1964), Zartman and others (1965), Brookins and Hurley

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(1965), Brookins (1965), and Fairbairn and others (1967), to mention only a few.[1]

Isotopic ages can be applied to the interpretation of the geology of a region only to a limited extent, because they usually represent minimum ages or apparent ages. In areas underlain by unfossiliferous metasedimentary rocks, the absolute age of the strata can only be inferred from long-range correlation with strata of known age and from the limits placed by the isotopic ages.

In areas where good geological control has been established, the rubidium-strontium whole-rock isochron method of age determination has proven to be a most valuable tool for stratigraphic correlation.

The present investigation is a systematic age study in a region that has been involved in a series of metamorphic episodes. An attempt has been made to interpret the complex metamorphic history of the region and to relate the apparent times of metamorphism with igneous intrusion. The work consists chiefly of K-Ar apparent ages on separated minerals.

Rb-Sr whole-rock and mineral isochrons have been obtained for the Waterbury gneiss in western Connecticut in an attempt to establish a more reliable minimum age for the rocks of the Waterbury dome and for an intrusive porphyry near Bridgeport in southwestern Connecticut in an attempt to establish an upper limit for pre-Triassic intrusion in western Connecticut.

## BRIEF DISCUSSION OF REGIONAL GEOLOGY

*Manhattan prong.*—A generalized geologic map of the region is presented in figure 3. The metamorphosed sedimentary rocks of the Manhattan prong consist of medium- to high-grade schist and gneiss and marble. The area is bordered on the west by the Hudson River, on the south by Long Island Sound, on the east by an adjoining metamorphic region, which extends eastward into Connecticut, and on the north by the Hudson Highland gneiss of Precambrian age. The rocks have a northeasterly trend and extend into western Connecticut, terminating against the Precambrian basement rocks of the highlands near Danbury.

Isachsen (1964) has presented the following stratigraphic sequence from information gained from several sources:

| | |
|---|---|
| Ordovician? | Cortlandt mafic complex |
| Cambro-Ordovician? | Manhattan formation<br>Inwood marble, locally with Lowerre quartzite at base |
| Precambrian? | Fordham gneiss<br>Yonkers granitic gneiss |

The problem of most concern to workers in the area is whether or not any of the units are Precambrian. Although extensive work has been

[1] Reports of current radiometric investigations in New England appear in the M.I.T. age studies progress reports for 1966 and 1967.

done on the geology, the absence of fossils and the complex metamorphism have resulted in considerable controversy in assigning ages to the units.

Clarke (1958), working in the Danbury quadrangle of west-central Connecticut, and Prucha (1956), working in Putnam and Westchester Counties, N.Y., found that "Fordham-type" gneiss also occurs within "Manhattan-type" gneiss and that these two units may alternate stratigraphically or may be infolded into one another. Hall (1966), working in the vicinity of Tarrytown, N.Y., has revealed a folded unconformity whereby the large-scale fold system of the Fordham gneiss is truncated by the younger stratigraphic sequence; Lowerre quartzite–Inwood formation–Manhattan formation, thus defining two distinct episodes of deformation.

Near Peekskill, N.Y. and in western Connecticut, the Manhattan prong has been intruded by younger granite. Numerous pegmatites also cut the prong rocks.

In general, the structure in Manhattan, the Bronx, and Westchester County is that of isoclinal folds with northeast striking axial planes. These folds have later been refolded into great arcs, again suggesting at least two periods of metamorphism (Scotford, 1956).

West of Danbury, Conn., the Highlands border fault marks the boundary of this sequence with the Highlands gneiss, and the rocks of the Precambrian Highlands have been thrust eastward and southward over the rocks of the Manhattan prong (Clarke, 1958). Isachsen (1964) believes the Yonkers granitic gneiss is a metasedimentary unit underlying the Fordham gneiss and supports the belief that both units are possibly Precambrian.

*Western Connecticut.*—Western Connecticut (west of the Central Triassic Lowland) is underlain chiefly by a sequence of metamorphic rocks derived, for the most part, from preexisting pelitic or semi-pelitic sedimentary rocks of uncertain age. Granitic to dioritic intrusions and pegmatites are common.

Rodgers, Gates, and Rosenfeld (1959) have divided the pre-Triassic rocks into three main belts of metamorphic rocks having a general northeast trend. Figure 1 is a part of their generalized tectonic map of Connecticut. The boundaries separating the three belts have not been completely defined. These belts are the northwestern belt, the central belt, and the southeastern belt.

The northwestern belt consists of the Precambrian basement rocks of the Hudson, Housatonic, and Berkshire Highlands and a possibly early Paleozoic belt of high-to-medium grade schist and gneiss represented chiefly by the Waramaug formation, and in general probably represents the northeastern continuation of the Manhattan prong and the Hudson Highlands. Since the rocks of this belt have not been included in the present study, they are not discussed here.

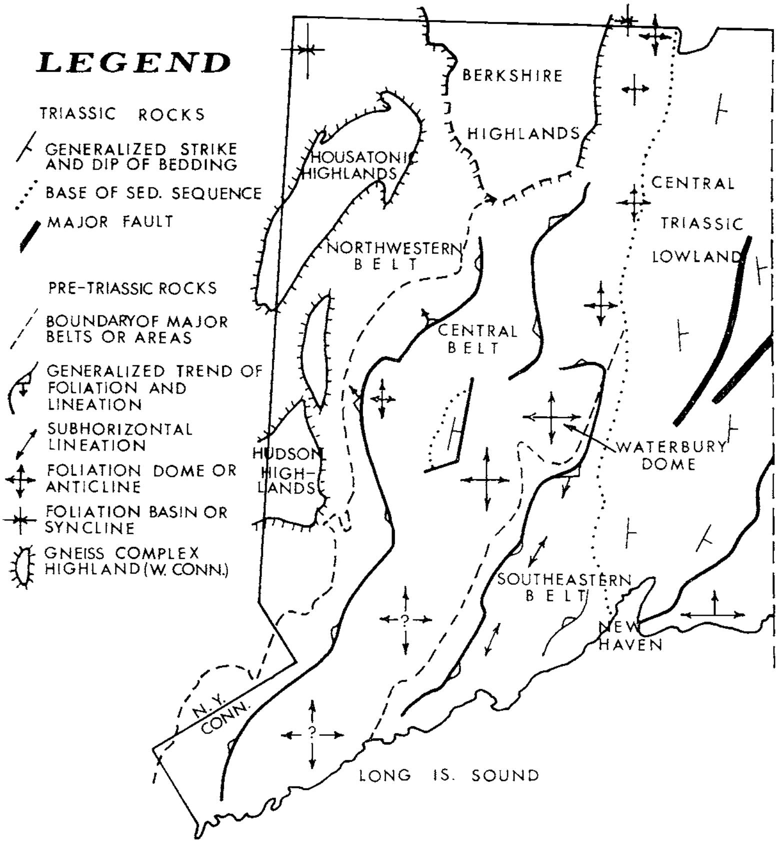


Fig. 1. Tectonic map of western Connecticut (after Rodgers, Gates, and Rosenfeld, 1959).

The central belt comprises a complex assemblage of metasedimentary rocks cut by syn- to post-tectonic intrusions ranging in composition from peridotite to granite. The belt, extending from Long Island Sound in southeastern New York northeast into Massachusetts, consists chiefly of a group of medium-grade metasedimentary rocks historically considered as the Hartland formation but currently being subdivided into several lithologic units as detailed mapping progresses (for example, Stanley, 1964; Cassie, ms; Gates and Christensen, 1965; Gates and Martin, 1967). Regionally, the northern continuation of the Hartland formation lies on the east flank of the Green Mountain anticlinorium. Syntectonic to post-tectonic granites and pegmatites occur throughout western Connecticut. The granites include the discordant Nonewaug granite (Gates, 1954; Gates and Scheerer, 1963), which is interpreted as being post-orogenic, and the Roxbury granite gneiss, which was probably intruded at a late stage of deformation (Gates, 1959).

Among the more mafic types of intrusions are the Brookfield diorite gneiss and the Harrison granodiorite gneiss. Associated with all members of the Hartland formation are amphibolites which are considered to be basic intrusions that accompanied orogeny and metamorphism (Gates, 1967).

Structurally, the Hartland formation is an isoclinally folded series of metasedimentary rocks which have been refolded late in their tectonic and metamorphic history. The geological age of the Hartland formation is in doubt. It is considered younger than the Waramaug (Gates, 1952) and is generally correlated with the Hoosac-Rowe-Savoy sequence in Massachusetts, in which case it could not be younger than Middle Ordovician.

In the southeastern belt, northwest of New Haven, Rodgers, Gates, and Rosenfeld (1959) described the following sequence of units from southeast to northwest:

Milford chlorite schist
Orange phyllite
Prospect gneiss
Straits schist member of the Hartland formation
Waterbury gneiss

The geologic map of this belt accompanying the present paper (fig. 3) is quite generalized, and a more detailed account is presented by Fritts (1962; 1963a,b; 1965a,b). Geologic ages ranging from Precambrian (Waterbury gneiss) to Silurian and Devonian (Orange phyllite) have been assigned to the metasedimentary and metavolcanic sequence in the southeastern belt on the basis of correlation with an established stratigraphic succession in southeastern Vermont. The Waterbury gneiss dome is the southernmost of a series of gneiss domes extending from Chester, Vt., to Waterbury along the eastern flank of the Green Mountain anticlinorium. The Waterbury formation (Gates and Martin, 1967) is a paragneiss complex forming the core of the dome. The age of the Waterbury formation and the role of the core of the dome in producing the structures of the mantling rocks is still unresolved.

## PREVIOUS ISOTOPIC AGE STUDIES

The isotopic age studies done in western Connecticut prior to the present investigation were only reconnaissance work. This work was confined to pegmatites until recently. Rodgers (1952) and Goldsmith (1964) summarize the older work. Pegmatites had been dated at Branchville, Conn., using uraninite (Wasserburg, Hayden, and Jensen, 1956), and at Bedford, N.Y., using Pb/U isotopic ratios from cyrtolite (Nier, 1939). Concordant ages of about 365 and 350 m.y. respectively were obtained. Later work (Wasserburg, Hayden, and Jensen, 1956) by the potassium-argon method was in good agreement. These measurements gave the first indication as to the time of metamorphism in the region.

In the Middletown area of eastern Connecticut earlier work by Nier, Thompson, and Murphy (1941), Wasserburg, Hayden, and Jensen (1956), Wasserburg and Hayden (1955), and Eckelmann and Kulp (1957) showed that the age of emplacement of pegmatites occurred about 255 m.y. ago. Subsequent K-Ar age measurements on micas (Zartman and others, 1965) from eastern Connecticut are all quite uniform, yielding ages of about 240 m.y., suggesting a culmination of metamorphism in eastern Connecticut in the Permian.

The metamorphic history of the Manhattan prong rocks (Long and Kulp, 1958, 1962; Long, Cobb, and Kulp, 1959) and the metamorphic belt in Dutchess County to the north (Long, 1962) have been investigated in detail by isotopic age methods. It was found that a major metamorphic event affected the Manhattan prong about 360 m.y. ago. This event was accompanied by widespread pegmatite intrusion. The narrow spread of the K-Ar apparent ages around 360 m.y. is striking.

However to the northwest in the prong, a number of remnant dates were found, the highest of which is 480±15 m.y. on biotite from the Fordham gneiss at Crotonville, N.Y. As Isachsen (1964) points out, the occurrence of the older remnant ages to the northwest is significant since the regional metamorphic grade is lower to the west, and less complete resetting of an older age should occur there. In any case, a Cambro-Ordovician age for the Fordham gneiss was not ruled out. Since, however, the 480 m.y. date represents a minimum age for the initial metamorphism, and a sedimentary cycle must have preceded this metamorphic event, it does appear that the initial deposition of the Fordham gneiss was pre-Ordovician.

In the present study, an attempt has been made to interpret the apparently complex metamorphic history of western Connecticut and northeastern New York chiefly by the potassium-argon dating of mica and hornblende and to establish a minimum age for the metasedimentary sequences that underlie these regions.

## RESULTS AND DISCUSSION OF AGE DETERMINATIONS

*General statement.*—The analytical procedures used in the present study are discussed elsewhere (Clark, ms). Sample locations and brief petrographic descriptions are presented in the Appendix (see Clark, ms, for more detailed sample descriptions). The K-Ar ages are listed in table 1. Figures 2 and 3 give the sample locations and age distribution respectively for the K-Ar results. The Rb-Sr analytical results for the Waterbury gneiss and the intrusive porphyry are listed in tables 2 and 3 respectively, and the corresponding isochron plots are given in figures 5 and 6. The two locations where samples for the Rb-Sr work were collected are shown in figure 3.

*K-Ar results and discussion.*—Replicate K-Ar determinations and the uncertainty in the spike calibrations yield an overall error for the $Ar^{40}/K^{40}$ ratio of about ±2 percent. An error of ±4 ($2\sigma$) is quoted in the results.

TABLE 1

Potassium—argon analytical results

| Sample | K(%) | Radiogenic $Ar^{40}$ (ppm) | Radiogenic $Ar^{40}$ / Total $Ar^{40}$ | Apparent Age (m.y.) | Description* |
|---|---|---|---|---|---|
| L–853H | 4.73 | 0.163 | 0.96 | 430 ± 16 | Fordham gneiss |
| L–857H | 1.50 | 0.0366 | 0.95 | 315 ± 12 | Fordham gneiss |
| L–858H | 1.02<br>1.00 | 0.0281 | 0.97 | 310 ± 12 | Fordham gneiss |
| L–858B | 7.24 | 0.175 | 0.86 | 310 ± 12 | Fordham gneiss |
| L–860M | 7.38 | 0.186 | 0.80 | 320 ± 12 | Biotite–muscovite schist |
| L–861H | 1.01 | 0.0218 | 0.94 | 285 ± 11 | Hornblende–biotite gneiss |
| L–864B | 7.54 | 0.117 | 0.79 | 295 ± 11 | Biotite–muscovite schist |
| L–865M | 7.87 | 0.202 | 0.82 | 330 ± 13 | Biotite–muscovite schist |
| L–866B | 8.08<br>8.17 | 0.187 | 0.80 | 305 ± 12 | Pegmatite |
| L–867M | 8.82 | 0.212 | 0.85 | 310 ± 9 | Granite gneiss |
| L–870M | 8.50 | 0.194 | 0.93 | 290 ± 8 | Muscovite–biotite schist |
| L–872M | 9.11 | 0.200 | 0.95 | 285 ± 11 | Granite gneiss |
| L–873B | 6.63 | 0.130 | 0.95 | 255 ± 10 | Biotite schist |
| L–874B | 7.22 | 0.158 | 0.91 | 285 ± 11 | More massive unit in schist of L–873 |
| L–875B | 5.30 | 0.127 | 0.85 | 265 ± 11 | Hornblende–biotite gneiss |
| L–875H | 0.526<br>0.527 | 0.0173 | 0.77 | 415 ± 16 | Hornblende–biotite gneiss |
| L–879M | 8.67 | 0.157 | 0.92 | 240 ± 10 | Branford granitic gneiss |
| L–881M | 8.73 | 0.220 | 0.91 | 325 ± 13 | Pegmatite associated with L–879 |
| L–882M | 7.40 | 0.160 | 0.88 | 280 ± 11 | Orange phyllite (Derby Hill schist of Fritts 1965b) |
| L–980B | 7.91 | 0.185 | 0.89 | 305 ± 12 | Granite gneiss |
| L–981B | 7.68 | 0.199 | 0.92 | 335 ± 13 | Biotite schist |
| L–982B | 7.55 | 0.185 | 0.94 | 315 ± 13 | Hornblende–biotite gneiss |
| L–983B | 7.20 | 0.167 | 0.94 | 315 ± 13 | Fordham gneiss |
| L–984B | 6.64 | 0.193 | 0.92 | 370 ± 15 | Fordham gneiss |
| L–985B | 5.72 | 0.162 | 0.94 | 360 ± 14 | Fordham gneiss |
| L–986B | 6.79 | 0.178 | 0.94 | 335 ± 13 | Fordham gneiss |
| L–987H | 1.00 | 0.0310 | 0.81 | 395 ± 16 | Fordham gneiss |
| L–988B | 7.33 | 0.188 | 0.89 | 330 ± 13 | Hornblende–biotite gneiss |
| L–989B | 6.45 | 0.139 | 0.92 | 280 ± 11 | Granite gneiss |
| L–990B | 6.44 | 0.125 | 0.89 | 255 ± 10 | Biotite schist (weathered) |
| L–991B | 5.42 | 0.114 | 0.88 | 275 ± 10 | Granite gneiss |
| L–992B | 7.24 | 0.180 | 0.92 | 320 ± 13 | Biotite schist (weathered) |
| L–993B | 7.05 | 0.180 | 0.93 | 330 ± 13 | Manhattan formation |

TABLE 1 (Continued)

| Sample | K(%) | Radiogenic $Ar^{40}$ (ppm) | Radiogenic $Ar^{40}$ / Total $Ar^{40}$ | Apparent Age (m.y.) | Description* |
|---|---|---|---|---|---|
| L–994B | 6.24 | 0.219<br>0.220 | 0.97<br>0.92 | 440 ± 17 | Manhattan formation |
| L–995B | 6.91 | 0.187 | 0.87 | 345 ± 14 | Manhattan formation |
| L–996B | 6.71 | 0.191<br>0.196 | 0.95<br>0.94 | 370 ± 15 | Biotite–garnet gneiss |
| L–997B | 7.18 | 0.227 | 0.84 | 400 ± 16 | Fordham gneiss |
| L–998B | 6.74 | 0.176 | 0.76 | 335 ± 13 | Biotite gneiss (weathered) |
| L–1001B | 7.47 | 0.191 | 0.94 | 330 ± 13 | Hornblende–biotite gneiss |
| L–1001H | 0.847 | 0.0240 | 0.64 | 360 ± 14 | Hornblende–biotite gneiss |
| L–1002B | 7.66 | 0.186 | 0.92 | 305 ± 12 | Mica quartzite |
| L–1003B | 6.52 | 0.131 | 0.84 | 265 ± 11 | Biotite schist |
| L–1004B | 7.44 | 0.148 | 0.91 | 260 ± 10 | Augen gneiss |
| L–1005B | 5.25 | 0.133 | 0.91 | 325 ± 13 | Augen gneiss |
| L–1006B | 8.03 | 0.185 | 0.92 | 315 ± 12 | Biotite schist |
| L–1008B | 6.76 | 0.134 | 0.86 | 260 ± 10 | Biotite schist (weathered) |
| L–1009B | 5.80 | 0.143<br>0.141 | 0.88<br>0.80 | 310 ± 13 | Augen gneiss |
| L–1010B | 6.78 | 0.179 | 0.91 | 340 ± 14 | Biotite gneiss |
| L–1011B | 4.87 | 0.117 | 0.73 | 325 ± 12 | Biotite–muscovite schist |
| L–1012B | 7.32 | 0.268 | 0.96 | 455 ± 18 | Fordham gneiss |
| L–1088H | 0.270<br>0.276 | 0.00787 | 0.51 | 370 ± 15 | Amphibolite |
| L–1089B | 7.11 | 0.194 | 0.95 | 350 ± 14 | Biotite gneiss |
| L–1090B | 4.31<br>4.32 | 0.110 | 0.85 | 330 ± 13 | Nonewaug granite |
| L–1090M | 8.78 | 0.244 | 0.85 | 355 ± 14 | Nonewaug granite |
| L–1092B | 7.24 | 0.202 | 0.95 | 355 ± 14 | Gray granulite** |
| L–1096B | 6.70<br>6.59 | 0.204<br>0.204 | 0.94<br>0.96 | 385 ± 15 | Reynolds Bridge gneiss |
| L–1096H | 1.14 | 0.0327 | 0.79 | 365 ± 14 | Reynolds Bridge gneiss |
| L–1098B | 7.98 | 0.209 | 0.82 | 335 ± 13 | Gray granulite** |
| | 8.00 | 0.213 | 0.86 | | |
| L–1099H | 0.479 | 0.0151 | 0.79 | 400 ± 16 | Amphibolite |
| L–1100B | 6.61 | 0.187 | 0.94 | 360 ± 14 | Biotite–chlorite schist |
| L–1101B | 6.57 | 0.182 | 0.94 | 335 ± 14 | Collinsville gneiss |
| L–1101M | 7.57 | 0.220 | 0.84 | 370 ± 15 | Undeformed pegmatite cutting Collinsville gneiss |
| L–1102H | 0.374 | 0.0117 | 0.64 | 395 ± 16 | Amphibolite |
| L–1103B | 6.11<br>6.01 | 0.165 | 0.93 | 345 ± 13 | Biotite–chlorite schist |
| L–1104aB | 5.77<br>5.87 | 0.201<br>0.205 | 0.95<br>0.58 | 430 ± 17 | Biotite schist |

TABLE 1 (Continued)

| Sample | K(%) | Radiogenic $Ar^{40}$ (ppm) | $\frac{\text{Radiogenic } Ar^{40}}{\text{Total } Ar^{40}}$ | Apparent Age (m.y.) | Description* |
|---|---|---|---|---|---|
| L–1104bH | 0.218<br>0.231 | 0.00704<br>0.00715 | 0.69<br>0.67 | 400 ± 16 | Amphibolite |
| L–1105B | 7.54 | 0.200 | 0.91 | 340 ± 13 | Roxbury granite gneiss |
| L–1106B | 7.37 | 0.209 | 0.94 | 365 ± 14 | Biotite gneiss |
| L–1107B | 6.58 | 0.204 | 0.96 | 395 ± 16 | Brookfield diorite gneiss |
| L–1108B | 7.73 | 0.189 | 0.76 | 315 ± 13 | Fordham gneiss |
| L–1109B | 6.15 | 0.165 | 0.94 | 345 ± 13 | Waterbury gneiss |
| L–1110H | 3.23<br>3.26 | 0.117<br>0.115 | 0.93<br>0.98 | 445 ± 18 | Yonkers gneiss |

H = Hornblende

B = Biotite

M = Muscovite

$\lambda\beta = 4.72 \times 10^{-10} yr^{-1}$; $\lambda e = 0.583 \times 10^{-10} yr$

* Brief description and location given in Appendix A.

** "Granulite" is here used as a textural term (Gates and Christensen, 1965, p.14)

The geological implications and the various problems involved in the interpretation of K-Ar ages have been discussed frequently in the literature, and only a few aspects are mentioned here.

The K-Ar ages reported in this work are considered reliable minimum ages. No evidence has appeared to suggest that the amount of primary $Ar^{40}$ incorporated into potassium-rich minerals that are at least 100 m.y. old is sufficient to affect the calculated age. The K-Ar isotopic ages may be lower than the geological age of the rocks because of elevated temperature during the history of the mineral. The effect of temperature on the argon retentivity of various minerals has been investigated, both in the laboratory and in the field (Amirkhanoff, Brandt, and Barnitsky, 1961; Evernden and others, 1960; Hanson and Gast, 1967; Hart, 1964; Catanzaro and Kulp, 1964). These results make it possible to estimate the sensitivity of biotite and muscovite to argon loss as a function of time and temperature.

The interpretation of K-Ar ages from a regionally metamorphosed area that has undergone more than one thermal event is complex. Absolute dates of crystallization can be identified only by concordance of several isotopic chronometers. If only two events exist in a region, the two dates may be ascertainable by the K-Ar method. The isotopic ages in between display the relative argon loss due to the temperature increase from the younger event.

The K-Ar apparent ages in the region range from 240 m.y. to 455 m.y. The published results of Long and Kulp (1962) clearly demonstrate that the Precambrian rocks in the New York Highlands are at least

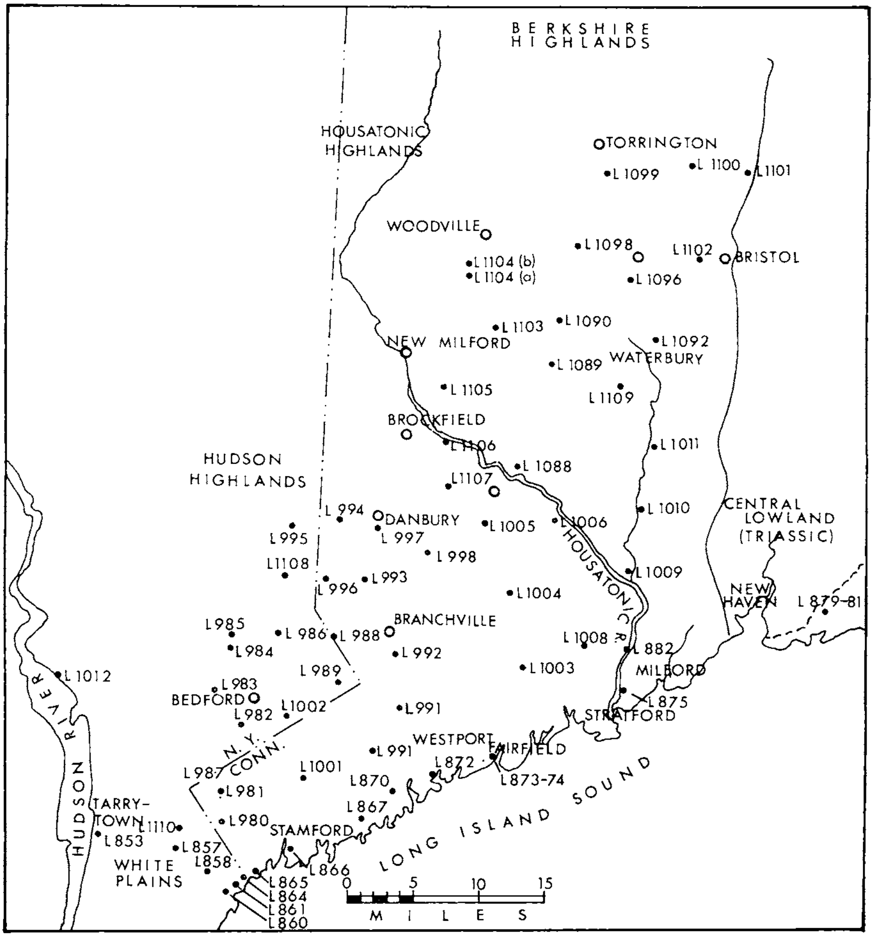


Fig. 2. Sample location map for K-Ar dates.

1000 m.y. old. The Manhattan prong rocks, including part of the sequence in western Connecticut, were probably deposited on this basement in late Precambrian time and/or during the Cambrian and early Ordovician time. The Fordham gneiss in the Manhattan prong sequence was metamorphosed at least 480 m.y. ago (pre-Trenton). Potassium-argon dates of 400 m.y. and older from the metamorphic sequence in westernmost Connecticut suggest these rocks were formed during the pre-Trenton event, since they appear to represent transitional isotopic ages only. There is no independent evidence of a thermal event in this area between 480 and 360 m.y. ago.

The first subsequent metamorphism to affect the region occurred about 360 m.y. ago. This age has been well established by previous work on pegmatites at Bedford, N.Y. and Branchville, Conn. (table 2). It

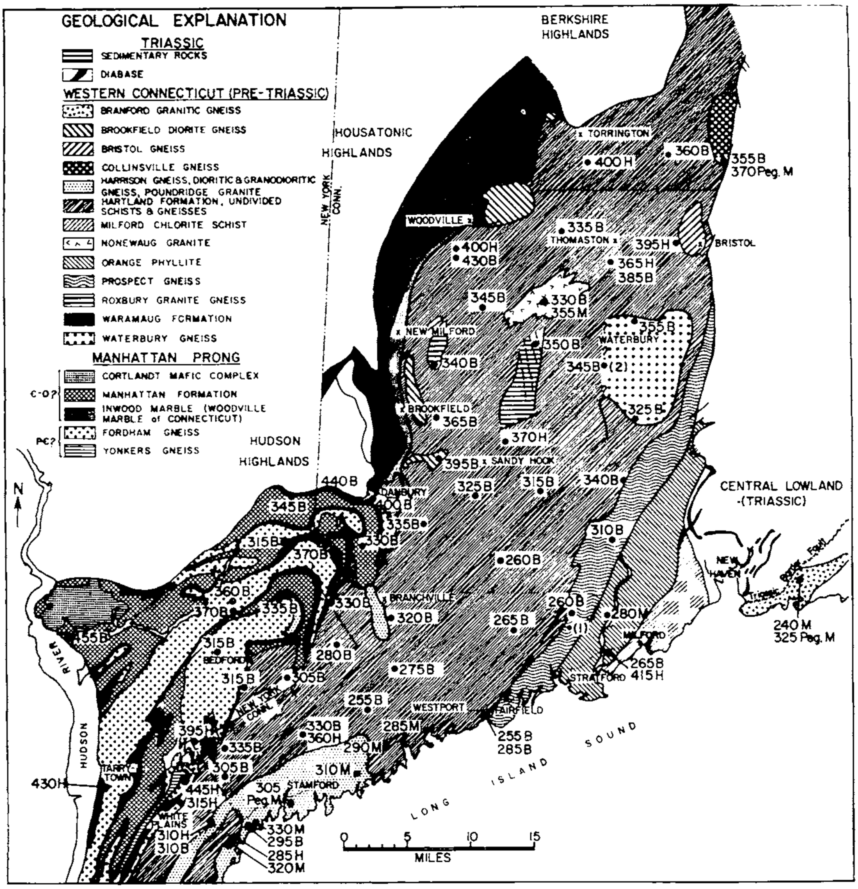


Fig. 3. K-Ar dates and generalized geological map of southeastern New York and western Connecticut. Rb-Sr sample locations included: (1) intrusive porphyry, (2) Waterbury gneiss. Geology compiled from the New York State geological map for 1961 and the preliminary geological map of Connecticut for 1959. B = biotite, M = muscovite, and H = hornblende.

should be stressed that this age is not a transition date but represents the age of emplacement of the pegmatites since concordant potassium-argon and uranium-thorium-lead ages have been obtained.

Similarly, reasonably concordant potassium-argon, rubidium-strontium, and uranium-thorium-lead ages from pegmatites at Glastonbury and Portland, Conn. (table 2) clearly show evidence for a second metamorphism about 255 m.y. ago. This younger event was more widespread in eastern Connecticut—affecting only part of the area west of the Triassic Basin.

Figure 4 is a generalized map showing the effect on the mica potassium-argon dates of the superimposed Paleozoic metamorphisms.

TABLE 2

Isotopic ages for pegmatites from Southeastern New York and Connecticut

| Locality | Mineral | Method | Age (m.y.) | Reference |
|---|---|---|---|---|
| Connecticut | | | | |
| Portland, Strickland Quarry | Uraninite | $Pb^{206}/U^{238}$ | 268 | Wasserburg and Hayden (1955) |
| | | $Pb^{207}/U^{235}$ | 266 | |
| | | $Pb^{207}/Pb^{206}$ | 250 | |
| | | $Pb^{208}/Th^{232}$ | 239 | |
| " | Muscovite | K/Ar | 255 ± 5 | Wasserburg, Hayden, and Jensen (1956)* |
| " | Muscovite | Rb/Sr | 255 ± 8 | Brookins (ms)** |
| | Microcline | Rb/Sr | 255 ± 8 | |
| Glastonbury, Spinelli Quarry | Samarskite | $Pb^{206}/U^{238}$ | 257 ± 3 | Eckelmann and Kulp (1957) |
| | | $Pb^{207}/U^{235}$ | 258 ± 3 | |
| | | $Pb^{207}/Pb^{206}$ | 292 ± 35† | |
| | | $Pb^{208}/Th^{232}$ | 257 | |
| " | Muscovite | K/Ar | 250 ± 5 | Wasserburg, Hayden, and Jensen (1956)* |
| " | Muscovite | Rb/Sr | 255 ± 8 | Brookins (ms)** |
| | Microcline | Rb/Sr | 255 ± 8 | |
| Bridgeport Quadrangle | Whole-rock-feldspar-biotite | Rb/Sr | 250 ± 5 | Intrusive porphyry, this work |
| Branchville | Uraninite | $Pb^{206}/U^{238}$ | 367 | Wasserburg, Hayden, and Jensen (1956)* |
| | | $Pb^{207}/U^{235}$ | 365 | |
| | | $Pb^{207}/Th^{232}$ | 318 | |
| | Muscovite | K/Ar | 369 ± 11 | " |
| | | K/Ar | 366 ± 11 | Long and Kulp (1962) |
| New York | | | | |
| Bedford | Cyrtolite | $Pb^{206}/U^{238}$ | 351 | Nier (1939)†† |
| | | $Pb^{207}/U^{235}$ | 355 | |
| | | $Pb^{207}/Pb^{206}$ | 389 | |
| | Cyrtolite | $Pb^{206}/U^{238}$ | 335 | Nier (1939)†† |
| | | $Pb^{207}/U^{235}$ | 345 | |
| | | $Pb^{207}/Pb^{206}$ | 423 ± 40 | |

* $\lambda\beta = 4.72 \times 10^{-10} yr^{-1}$; $\lambda = 0.583 \times 10^{-10} yr^{-1}$

** Recalculated using $\lambda Rb^{87} = 1.39 \times 10^{-11} yr^{-1}$

† Analytical error

†† Recalculated using new decay constants (Tilton, 1965)

TABLE 3

Rubidium–strontium results
Waterbury gneiss

| Sample | Rb(ppm) | Sr(ppm) | $Rb^{87}/Sr^{86}$ | $Sr^{87}/Sr^{86}$ Calculated | $Sr^{87}/Sr^{86}$ Normalized |
|---|---|---|---|---|---|
| L–1127 | 168.3 | 31.96 | 15.5 | 0.8004 | 0.8011 |
| | 166.8 | 32.40 | 15.0 | 0.8012 | 0.8012 |
| L–1128 | 118.4 | 106.9 | 3.21 | 0.7383 | 0.7397 |
| L–1129 | 95.65 | 166.3 | 1.67 | 0.7303 | 0.7303 |
| | 95.22 | 166.7 | 1.65 | 0.7283 | 0.7299 |
| L–1109(a) | 132.6 | 59.28 | 6.49 | 0.7594 | 0.7589 |
| L–1131 | 127.0 | 104.2 | 3.53 | 0.7353 | 0.7370 |
| L–1132 | 68.64 | 240.4 | 0.826 | 0.7150 | 0.7163 |
| L–1133 | 184.9 | 84.99 | 6.31 | 0.7569 | 0.7563 |
| L–1134 | 168.9 | 40.40 | 12.28 | 0.7906 | 0.7914 |
| L–1135 | 148.6 | 56.21 | 7.68 | 0.7654 | 0.7650 |
| L–1136 | 104.0 | 44.14 | 6.84 | 0.7615 | 0.7615 |
| | 103.8 | 43.92 | 6.86 | 0.7623 | 0.7623 |
| L–1137 | 77.8 | 413.1 | 0.545 | 0.7149 | 0.7140 |
| L–1128 Plagioclase and quartz | 18.09 | 93.22 | 0.629 | 0.7276 | 0.7291 |
| L–1128 K–feldspar | 188.4 | 407.3 | 13.4 | 0.8053 | 0.8053 |
| L–1109(a) Biotite | 441.2 | 3.88 | 366.9 | 2.000 | 1.993 |
| | 449.4 | 3.97 | 373.8 | 1.962 | 1.971 |
| L–1128 Muscovite | 270.1 | 16.59 | 47.69 | 0.8777 | 0.8770 |
| | 269.5 | | | | |

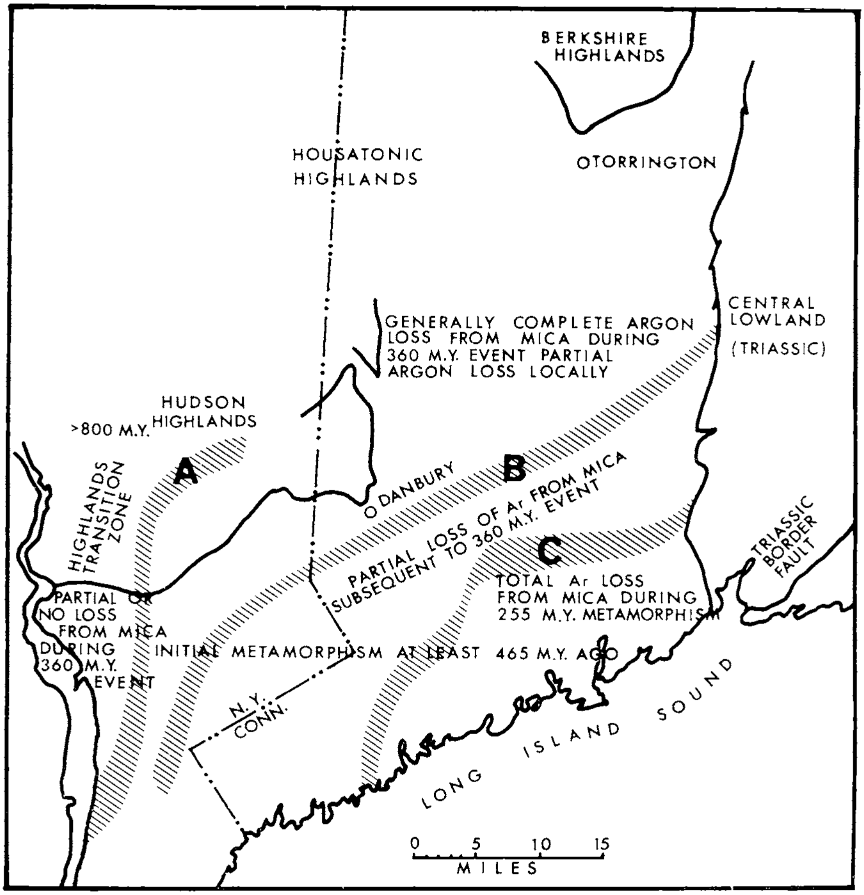


Fig. 4. Generalized map showing effect of superimposed metamorphic events on mica K-Ar ages. Compiled in part from Long and Kulp (1962).

In the present work, the oldest age obtained is 455 m.y. on biotite from the Fordham gneiss collected at Oscawana, N.Y., about 1 mile south of the Cortlandt mafic complex. It is noteworthy that by far the oldest ages for the Manhattan prong rocks have been obtained from the Fordham gneiss. These results suggest that the eastern part of the Manhattan prong has been affected by a later thermal event, about 360 m.y. ago. Therefore isotopic ages in the two northwestern zones (between boundaries A and B) shown in figure 4 are transitional, representing argon loss of rocks probably metamorphosed prior to 480 m.y. ago but reheated to varying degrees at about 360 m.y. ago.

Further southeast, in Connecticut, another transition occurs giving isotopic ages between 360 m.y. and 240 m.y. This eastern transition zone between boundaries B and C becomes more apparent from isotopic ages obtained from the broad zone of undivided schist and gneiss included in the Hartland formation.

Of particular interest in the Manhattan prong is the 445 m.y. apparent age on hornblende from a sample of the Yonkers granitic gneiss taken from a quarry just north of White Plains, in Westchester County, N.Y. Isachsen (1964) considers it to be a metasedimentary unit underlying the Fordham gneiss and therefore probably Precambrian in age. Isachsen's interpretation is based on the unit's stratigraphic persistence, and the "intrusive" relations that occur can be explained by partial melting of the granitic material during high-grade regional metamorphism. Since slightly to the northwest in the same metamorphic sequence an age of 480 m.y. was obtained, this isotopic age of 445 m.y. is no doubt a minimum, and therefore it is probable that the Yonkers gneiss is also pre-Trenton. Whole-rock rubidium-strontium work on the Yonkers gneiss is currently underway (Long, written commun.), and initial results yield an isochron age of 570±15 m.y. and an initial $Sr^{87}/Sr^{86}$ ratio of 0.709±0.002[2]. These data refer to an early Cambrian or late Precambrian age for the Yonkers gneiss.

Ages younger than the 360 m.y. pegmatite ages are common from the country rock of the pegmatites; for example, the biotite apparent ages of 315 m.y. near Bedford from the Fordham gneiss, 320 m.y. from biotite schist south of Branchville, and 330 m.y. from a hornblende-biotite gneiss about 2 miles west of Branchville. Pegmatite ages older than those of their country rocks are common in many areas of the Appalachians and probably represent more reliable minimum ages for the time of metamorphism and intrusion. Similar evidence has been reported by Wetherill and others (1966) as a result of isotope age studies in the Maryland Piedmont, near Baltimore, Md. In rocks affected by a thermal event subsequent to pegmatite intrusion, the coarser pegmatite micas are less susceptible to argon loss than the generally finer mica in the country rocks. Northeast from the vicinity of Stamford, Connecticut, is an area yielding consistently younger potassium-argon ages. Previous work, mainly east of the Triassic Lowland, suggested that the 255 m.y. metamorphic area west of the lowland would be much more extensive. The question arises whether this area was involved in a later distinct metamorphism about 255 m.y. ago or whether the younger ages reflect a greater depth of burial and longer cooling history for this portion of the metamorphic complex. Rubidium-strontium data, to be discussed below, seem to imply the former explanation.

Two interpretations to relate the pattern of ages shown in figure 4 to the regional metamorphism are possible. First, subsequent to the 360 m.y. event, a northeast-trending thermal "front" might have moved southward or southeastward. The 360 m.y. thermal "event" would have terminated in southeastern Connecticut about 255 m.y. ago. Second, a

[2] Calculated at the 95 percent confidence level using $\lambda\ Rb^{87} = 1.39 \times 10^{-11} yr^{-1}$.

period of quiescence may have separated the 360 m.y. thermal event from a later, 255 m.y. metamorphism. In the second case, the question arises as to the orientation of the temperature front of the later event. If the temperature gradient was linear with distance from the metamorphic axis, a vertical thermal front on the northwest side of boundary C (fig. 4) would not produce the broad transition zone between boundaries B and C (the area of partial argon loss from mica subsequent to the 360 m.y. event), because the argon diffusion rate constant depends exponentially on temperature. If the second interpretation is correct, then the thermal plane probably dipped to the northwest.

These interpretations are quite speculative, since it is generally impossible to relate the complex age distributions in regionally metamorphosed terrains to specific temperature and time. Another parameter that should be considered is the mica grain size. However, in this case, a sufficiently large number of samples were dated to overcome the dependency of the age pattern on grain size.

To the north of boundary B, in Connecticut, the ages show strongly the influence of the 360 m.y. thermal event. An undeformed, crosscutting pegmatite in the Collinsville gneiss dome has been dated at 370 m.y. and in the Collinsville gneiss, itself, was dated at 355 m.y.—the two apparent ages agreeing within the experimental uncertainty of $\pm 4$ percent. Stanley (1964), from mapping in the Collinsville quadrangle and using regional geological evidence, suggests that the Collinsville dome was produced during the Acadian Orogeny (Middle and Late Devonian). The apparent age of 355 m.y. for the Collinsville gneiss supports Stanley's suggestion.

There are several types of intrusions in western Connecticut and some, like the Brookfield diorite gneiss, occur in belts within the Hartland formation. Potassium-argon apparent ages have been obtained on some of these.

The discordant Nonewaug granite has been called a late or post-tectonic intrusion (Gates and Scheerer, 1963) within the Hartland formation. The slightly discordant apparent ages—330 m.y. from biotite and 355 m.y. from a coarse muscovite—may be explained by the greater retentivity of muscovite for argon. Moreover, the granite may have been subjected to mild heating subsequent to intrusion, for the biotite sample analyzed did show an anomalously low potassium content (4.3 percent) as compared to most of the biotite studied, suggesting mild alteration. The 355 m.y. muscovite apparent age is considered to be the more reliable minimum age for the time of intrusion. This date is related to the 360 m.y. event discussed above, whereas the Hartland formation itself was metamorphosed at an earlier time, as indicated, for example, by the older remnant dates (400-430 m.y.) south of Woodville, south of Torrington, and west of Bristol. Long (1962) obtained a potassium-argon apparent age of $325 \pm 13$ m.y. on muscovite separated from the Nonewaug granite. This age is slightly outside the analytical error for the age reported here, although the samples are essentially from the same location.

Biotite separated from the Roxbury granite gneiss about 10 miles to the southwest was dated at 340 m.y. This rock has been described as a concordant intrusion, probably being intruded at a late stage of deformation (Gates, 1959)—the texture showing indications of cataclasis and recrystallization.

Extending northward along the western margin of the Hartland formation is the distinctive Brookfield plutonic series, well defined plutons of rocks ranging from diorite to granite. Some of the intrusive masses are composite (Clarke, 1958). The rocks are moderately to strongly foliated, and in many places have been affected by a post-crystallization shearing—the later deformation being parallel to the earlier one. Geological evidence suggests that the rocks were probably intruded early in the deformation—before the granites. Biotite from the Brookfield diorite gneiss about 5 miles northeast of Danbury was dated at 395 m.y.—significantly higher than the apparent ages obtained from the granites. It is concluded that this series of intrusions is indeed older than the granites and may have been intruded at the same time as the Cortlandt mafic complex near Peekskill, N.Y. A potassium-argon minimum age of 435 m.y. has been obtained on biotite from the Cortlandt complex (Long and Kulp, 1962).

A number of anomalously high dates have been obtained from the metamorphic schists and gneisses. For example, an apparent age of 415 m.y. was obtained from hornblende (sample L-875) separated from a lenticular amphibolite body lying within the Orange phyllite (Derby Hill schist of Fritts, 1965a,b) about 2.3 miles east of Stratford—on the Connecticut Turnpike—just east of the Housatonic River. Hence the minimum age of these rocks is 415 m.y. Fritts (1965a,b) has tentatively included the Derby Hill schist in the Middle Ordovician. Kulp (1961) places a date of 445 m.y. for the Trentonian, whereas Poole, Béland, and Wanless (1963) believe a date of 480 m.y. for the end of the Middle Ordovician is appropriate. The present isotopic data suggest that the rocks in the southeastern belt were metamorphosed during the 360 m.y. event and then reheated 255 m.y. ago. Although the anomalously high potassium-argon apparent age for the hornblende (biotite from the same sample gave an apparent age of $265 \pm 11$ m.y.) indicates a partial retention of argon and a closer approach to the true age, there is no independent evidence that rocks included in the Derby Hill schist were involved in a thermal event between 480 and 360 m.y. ago.

*Discussion of rubidium-strontium results.*—The data for the Waterbury gneiss are plotted in figure 5[3]. The samples analyzed were collected

[3] The $Rb^{87}$ decay constant proposed by Aldrich and Wetherill (1958), $1.39 \times 10^{-11}$ $yr^{-1}$, is used.

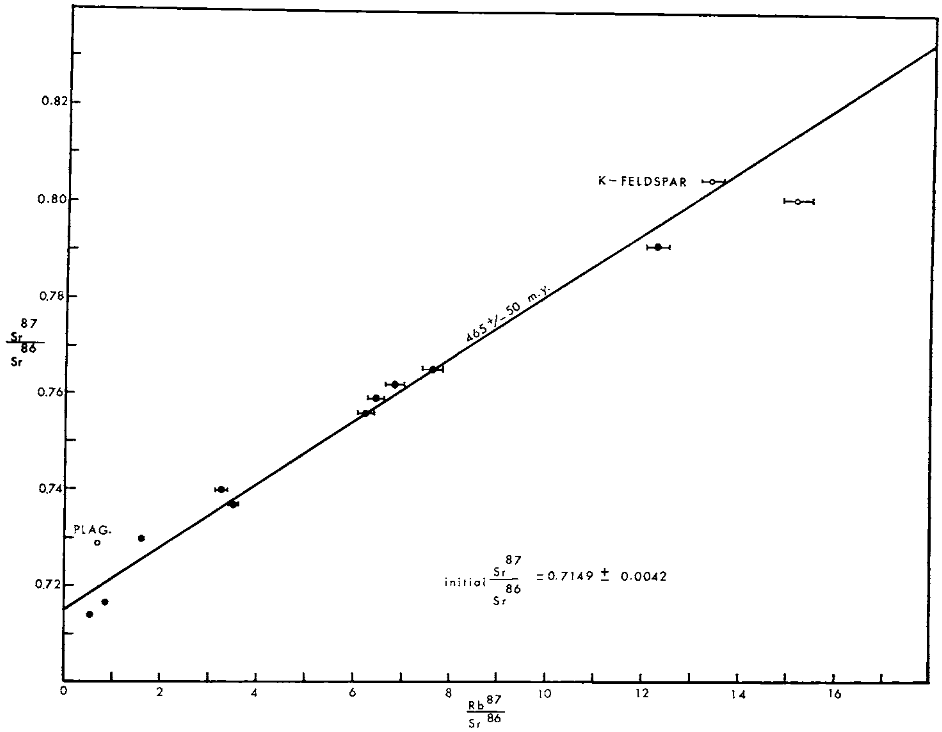


Fig. 5. Waterbury gneiss whole-rock apparent isochron. Solid points only used to construct isochron; explanation in text.

from the Waterbury formation—a metasedimentary gneiss complex forming the core of the Waterbury gneiss dome (Gates and Martin, 1967). The statistical model used to construct the isochrons is that recently proposed by McIntyre and others (1966) using a least squares regression method that incorporates previously determined estimates of the experimental errors for both the coordinates used to construct the isochrons and also makes allowance for the non-uniform variance in $Rb^{87}/Sr^{86}$. McIntyre's method also provides objective ways of detecting departures from the isochron model for any particular group of samples and for obtaining estimates of confidence intervals for their age and initial $Sr^{87}/Sr^{86}$ isotope ratio, and it is a more valid treatment of the data than the usual method of estimating isochrons by regression whereby the error on one of the coordinates is assumed to be negligible relative to the other.

The apparent age of the Waterbury gneiss as determined from the whole-rock data is $465 \pm 50$ m.y., with an initial $Sr^{87}/Sr^{86}$ isotope ratio of $0.7149 \pm 0.0042$ using 95 percent confidence limits. All the whole-rock data points and the points for the two feldspars are shown in figure 5. However, one whole-rock sample, L-1127, was omitted in the construction of the isochron, and the feldspars also were not used. Sample L-1127 falls below the isochron, and it is assumed that this sample was more affected by a subsequent metamorphism and was more susceptible either to loss of radiogenic $Sr^{87}$ or to gain of rubidium. This sample does have the highest Rb/Sr ratio of the whole-rock samples analyzed. Petrographic analysis also shows this sample to have the highest chlorite content, the chlorite obviously forming at the expense of the biotite.

The data points used to construct the isochron are not colinear, as could be expected since the Waterbury gneiss is considered to be metasedimentary and has been involved in more than one metamorphic episode. Biotite separated from one of the samples collected gave a potassium-argon apparent age of $345 \pm 13$ m.y. Also, many phases of the Waterbury formation are chlorite-bearing, suggesting that the gneiss was affected, subsequent to an earlier intense metamorphism, by retrograde effects. To minimize the effect of the inhomogeneity of the gneiss, the sample collection was restricted to a small area. The plagioclase and potash feldspar were analysed in order to gain some idea of the effect, if any, of the later metamorphism on these mineral phases. Subsequent metamorphism does not seem to have affected the potash feldspar since the results for the potash feldspar appear to fall on the whole-rock isochron, but the results for the plagioclase indicate subsequent partial redistribution of strontium. However, to get a better assessment of the effect of later metamorphism, it would be necessary to study more feldspar separates.

Perhaps one of the greatest problems concerning the Waterbury dome is whether or not it represents the Precambrian basement in this area. Information bearing on the age of the Waterbury formation is reviewed by Gates and Martin (1967, p. 14). The rubidium-strontium data reported here does not give sufficient information in this regard. The apparent age of $465 \pm 50$ m.y. probably represents a major metamorphism at that time and could be the initial metamorphism of the original sedimentary rocks. In any case, this interpretation of the age is consistent with the higher potassium-argon dates reported in the region, particularly for the Manhattan prong rocks, and does help to confirm the assumption that these rocks were involved in the Taconic disturbance on a large scale. It seems quite reasonable to place a minimum age of about 465 m.y. on the Waterbury gneiss on the basis of the potassium-argon ages. Therefore, initial metamorphism could have occurred in the interval $465 \pm 515$ m.y. ago taking into account the error on the whole-rock isochron of $\pm 50$ m.y.

Another possible interpretation of the whole-rock rubidium-strontium age for the Waterbury gneiss is that it could represent the original age of deposition of the sediments. If this is so, then the initial $Sr^{87}/Sr^{86}$ isotope ratio of $0.7149 \pm 0.0042$ is significantly higher than the value of 0.7093 reported for ocean water (for example, Faure, Hurley, and Powell, 1965). However, the initial ratio could conceivably be this high, depending on the provenance of the original sediment and the amount of inherited radiogenic $Sr^{87}$ from detrital material contained in the sediment. Again, however, the high potassium-argon ages in the region suggest that 465 m.y. is a minimum age for the initial metamorphism, and therefore the original age of the rock is somewhat older than this.

On the other hand, evidence to suggest a Grenville-type age for the original deposition of the sediments is absent. For example, if the original age for the sediments is assumed to be 1.0 b.y., then the average Rb/Sr ratio could not have been greater than about 0.5 (this estimate is made using an assumed initial $Sr^{87}/Sr^{86}$ isotope ratio of 0.702 which is probably the minimum approximation in this case). The locality sampled for the present study appears to include chiefly gneiss and schist derived for the most part from pelitic to semi-pelitic sedimentary rocks. Rubidium and strontium analyses show that the Rb/Sr ratio probably averages between 1 and 2. If the original age is about 1.0 b.y., then there would have had to be extensive changes in the Rb/Sr ratio at the time of metamorphism (for example, alkali metasomatism). However, the above approximation does not preclude a younger Precambrian age (600-700 m.y.) for the original deposition of the sediments.

Rubidium-strontium apparent ages were obtained from a biotite separated from sample L-1109(a) and a muscovite from sample L-1128 of the Waterbury gneiss. The calculated ages using the initial $Sr^{87}/Sr^{86}$ isotope ratio as determined from the isochron are concordant at $250\pm7$ and $245\pm10$ m.y. respectively. The discordance of these ages with respect to the potassium-argon apparent age of 345 m.y. for biotite from sample L-1109 is striking. Discordant ages reported in the literature commonly have shown the rubidium-strontium ages to be somewhat lower for biotite but not for muscovite. The muscovite strontium result has not been checked by a replicate determination, and the possibility of analytical error should not be ruled out.

Rubidium-strontium biotite ages may be lowered relative to the potassium-argon age as a result of preferential removal of radiogenic strontium and/or the addition of rubidium (Kulp and Engels, 1963; Goldich and Gast, 1966). The 250 m.y. biotite age possibly reflects the later retrograde effect discussed above. The correlation of the Waterbury dome with the mantled gneiss domes in southeastern Vermont has been considered. However, the Waterbury dome is more variable in lithology and further detailed geology is necessary before a correlation is warranted. Also, it has been shown that structurally similar domes in New England need not have had a similar origin.

The Lebanon and Mascoma (Oliverian) granitic domes in central New England give whole-rock rubidium-strontium isochron ages of 400 to 440 m.y. (Naylor and Wasserbury, 1966) with an initial $Sr^{87}/Sr^{86}$ isotope ratio of 0.706. The data indicate that these granite bodies cannot have been derived in a simple way from preexisting Precambrian basement rocks.

From the present data, the possibility that the Waterbury gneiss is Precambrian has not been ruled out. However, it is concluded that the Waterbury dome rocks were involved in a major metamorphism in the range 465 to 515 m.y. ago.

An acid porphyry intrusion in southwestern Connecticut was investigated by the rubidium-strontium method in order to obtain an estimate for the upper limit of pre-Triassic intrusion in western Connecticut. The data points for the intrusive porphyry are plotted in figure 6. The body lies within the Bridgeport quadrangle and is roughly circular in plan. Because of the very small areal extent of this body and its pronounced uniformity, the samples collected had similar Rb/Sr ratios; hence only one of the whole-rock samples was analyzed, and it was, therefore, necessary to use separated plagioclase and microcline in constructing the isochron. A biotite separate was also analyzed. Using 95 percent confidence limits, the slope of the isochron, including the biotite, gives an age of 249±5 m.y. and an initial $Sr^{87}/Sr^{86}$ isotope ratio 0.7069± 0.0005.

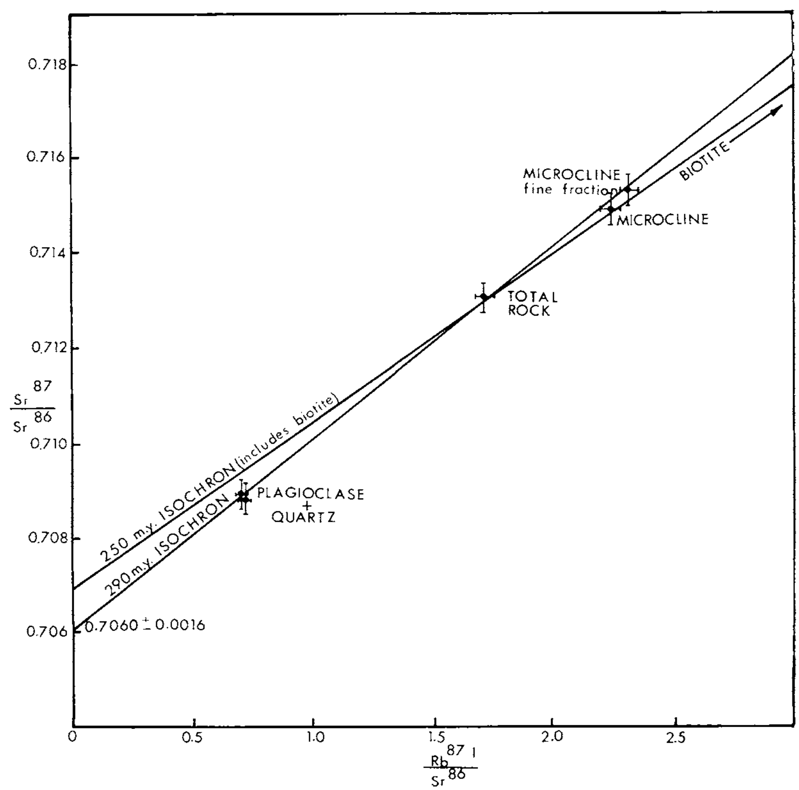


Fig. 6. Whole-rock and mineral isochron plot for the intrusive porphyry.

The isochron age using only the whole-rock and feldspar data points is 290±68 m.y., and the initial $Sr^{87}/Sr^{86}$ isotope ratio 0.7060±0.0016. Although these points are colinear, within the experimental error, the small spread in the $Sr^{87}/Sr^{86}$ isotope ratio (about 6 parts in 700) results in the large error on the age. The age of 250 m.y. is considered a reliable age for this intrusive body.

The intrusive porphyry is an undeformed, apparently shallow acid intrusion and appears to be post-metamorphic. The country rock in the area consists of strongly lineated biotite-hornblende gneiss. Potassium-argon apparent ages in the surrounding area range from 260 to 280 m.y. The rubidium-strontium data suggest that 250±5 is the most probable time for the pre-Triassic intrusion. These isotopic ages in southwestern Connecticut suggest that the area was involved in a limited episode of intrusion and local heating about 250 m.y. ago, coincident with that in eastern Connecticut.

## SUMMARY AND CONCLUSIONS

Potassium-argon apparent ages for mica and hornblende from a variety of metamorphic and plutonic rock types in southeastern New York and western Connecticut reflect the complex thermal and metamorphic history of this region. The isotopic ages range from 480 m.y. (as reported by Long and Kulp, 1962) for the Fordham gneiss unit of the Manhattan prong metamorphic sequence to 240 m.y. for the sequence in southwestern Connecticut. A complete range of isotopic ages between these limits has also been found. Previously reported results have shown the predominance of the 360 m.y. isotopic ages for most of the Manhattan prong sequence together with the common occurrence of older, remnant isotopic ages. This, coupled with reported pegmatite ages around 360 m.y. is consistent with the interpretation that these rocks were involved in a widespread metamorphism at this time that is, during the Acadian orogenic cycle.

However, eastward in the Manhattan prong and extending into southwestern Connecticut, apparent ages significantly lower than 360 m.y. show the influence of a later thermal event.

Isotopic ages in the range of 260 m.y. occur in a narrow belt of variable width from the vicinity of Stamford in southwestern Connecticut northeastward to the Central Triassic Lowland. The only evidence for possible late intrusion in this area of 260 to 280 m.y. potassium-argon ages is the 250±5 m.y. whole-rock and mineral isochron age from an intrusive acid porphyry in the Bridgeport quadrangle.

Further north in western Connecticut a transition zone occurs between the 260 m.y. metamorphic area and an area yielding significantly older isotopic ages. From the potassium-argon apparent ages on the post tectonic Nonewaug granite and a late pegmatite in the Collinsville gneiss it is concluded that this area underwent a period of deformation and granite intrusion at least 360 m.y. ago. A significantly large number of ages in the metamorphic schist and gneiss in the area also support this conclusion. That the region underwent a major and widespread metamorphism much earlier than 360 m.y. ago is indicated from remnant potassium-argon ages throughout the region. It is concluded from these higher potassium-argon apparent ages that the earlier metamorphism probably occurred around 460 to 480 m.y. ago. Further support of this is given by the $465 \pm 50$ m.y. rubidium-strontium whole-rock isochron age obtained from one restricted locality of the Waterbury dome gneiss complex. Although the linear correlation of the isochron points is not particularly good, the age is attributed to a high-grade metamorphism about this time. Whether the Waterbury mantled gneiss dome is Precambrian remains unsolved, but it is at least 465 m.y. old. However, evidence to suggest a Grenville-type age (900-1000 b.y.) is absent unless extensive changes in the Rb/Sr ratio occurred at the time of metamorphism, for example, as a result of alkali metasomatism.

A pre-Trenton age can also be assigned to the Fordham gneiss and Yonkers granitic gneiss, and these units have been metamorphosed at least 450 m.y. ago.

Field evidence in western Connecticut suggests that a number of the amphibolite bodies were emplaced before the granitic types. The potassium-argon dates on hornblende from a number of these bodies, for example, one from the New Preston quadrangle and two other occurrences near East Litchfield and near Milford, clearly show these bodies were emplaced at least 400 m.y. ago.

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## Appendix

## Locations and brief descriptions of samples

Detailed petrographic descriptions of the following samples are presented by Clark (ms).

*L-853:* Fordham gneiss. Collected at Interchange 8 (Elmsford, N.Y.) on Interstate 287 (eastbound): Hornblende-plagioclase gneiss—outcrop cut by numerous dikes both deformed and later cross-cutting ones. Hornblende separate essentially pure and unaltered in appearance.

*L-857:* Fordham gneiss. 0.4 mile west of exit of N.Y. Route 100A, White Plains (on Interstate 287): Microcline-hornblende-biotite gneiss. Essentially pure hornblende separate. Biotite separate 98 percent pure, unaltered with no visible chlorite.

*L-858:* Plagioclase-hornblende-biotite gneiss. Interstate 287 East at exit to N.Y. Route 120 (White Plains, N.Y.). No visible biotite in hornblende separate; 99 percent pure. Trace of aggregate.

*L-860:* Muscovite-biotite schist. Sample collected at Exit 13 (Port Chester, N.Y.) eastbound to Connecticut Turnpike (Interstate 95). Muscovite separate nearly pure. 1 percent chlorite—no visible aggregate.

*L-861:* Feldspar-biotite-hornblende gneiss. 0.7 mile east of Exit 13 (Port Chester, N.Y.) on Interstate 95. Hornblende separate has 2 percent aggregate. No visible biotite.

*L-864:* Biotite-muscovite-feldspar schist. 0.1 mile east of Greenwich, Conn., toll gate on Interstate 95. Large roadcut, moderately altered pelitic schist. Biotite separate has about 1 percent aggregate.

*L-865:* Muscovite schist. Collected about 0.2 mile east of L-864. Same continuous outcrop. Separated muscovite is nearly pure. Trace of aggregate.

*L-866:* Pegmatite lens in hornblende gneiss. 3.2 miles east of L-864 on Interstate 95. Coarse biotite separate; pure.

*L-867:* Coarse-grained granitic gneiss. 3.8 miles east of Exit 7 (Stamford) on Interstate 95, Conn. Muscovite separate is about 98 percent pure. Aggregate with 1 percent biotite.

*L-870:* Biotite-muscovite-garnet schist. 3.4 miles west of Norwalk, Conn., toll gate (east on Interstate 95). Separated muscovite is about 95 percent pure with aggregate and minor biotite; iron oxide coloring some of the grains.

*L-872:* Granitic gneiss. 0.4 mile east of Norwalk toll gate (Interstate 95). Muscovite separate about 98 percent pure with about 2 percent aggregate and biotite.

*L-873:* Garnet-staurolite-mica schist. 0.6 mile east of Exit 19 on Interstate 95. Reddish-brown biotite separate; about 2 percent aggregate.

*L-874:* This is a more massive bed in the schist of L-873. No discernible banding in thin section. Separated biotite is nearly pure. 1 percent aggregate with trace of chlorite.

*L-875:* Amphibolite. 2.3 miles east of Stratford toll gate, at Exit 35 (Interstate 95) just east of the Housatonic River. This is a hornblende gneiss body in the Orange phyllite (Derby Hill schist). Separated hornblende shows trace of biotite with less than

1 percent aggregate. Biotite fraction is about 95 percent pure, about 3 percent aggregate, and 2 percent hornblende.

*L-879:* Branford granitic gneiss. 1.9 miles east of Branford toll house in Interstate 95. Essentially pure muscovite separate. No visible aggregate. Trace of biotite.

*L-881:* Large pegmatite lens in L-879. Coarse book muscovite separated. The feldspars show the effect of extreme cataclasis. Muscovite has about 2 percent aggregate feldspar and quartz.

*L-882:* Muscovite-biotite schist (Derby Hill schist). On Merritt Parkway (west) just west of the Housatonic River before exit to Connecticut 110. Chlorite, biotite, and muscovite intimately intergrown. Separated muscovite is about 98 percent pure. Two percent intergrown biotite and trace of aggregate.

*L-980:* Granitic gneiss. Conn., 0.7 mile east of State Highway 120A on Sherwood Avenue, Greenwich. Separated biotite is essentially pure and unaltered. 1 percent aggregate.

*L-981:* Biotite-muscovite-garnet schist. Collected near Quaker Ridge, Conn., on John St., 0.3 mile east of Riversville Road, Greenwich. Medium-grained, gray-brown, weathered biotite schist. No visible chlorite in separated biotite. 1 percent aggregate. Some biotite grains show signs of possible alteration.

*L-982:* Biotite-hornblende gneiss. Sample collected along Banksville Road, about 2½ miles south of Bedford village, N. Y., 0.2 mile north of intersection to Hickory Kingdom Road. Separated biotite appears unaltered. About 1 percent aggregate.

*L-983:* Quartz-feldspar-biotite gneiss. Near Bedford village, N. Y., on Gerard Hill Road, between Baldwin and Succabone Roads. Medium-grained weathered gneiss showing highly cataclastic texture. The biotite is locally altered to chlorite and magnetite. Some of the biotite grains in the separate appear altered. About 2 percent aggregate, about 3 percent chlorite.

*L-984:* Biotite-hornblende-plagioclase (Fordham) gneiss. Collected on Jay St., 0.5 mile south of Reservoir Road near Katonah, N. Y. Separated biotite appears unaltered and is essentially pure.

*L-985:* Hornblende-biotite (Fordham) gneiss. Collected along N. Y. Route 45 just at northeast end of Cross River Reservoir near Katonah. Biotite has been locally replaced by magnetite with only a trace of chlorite. Separated biotite appears very fresh. No visible chlorite—about 5 percent aggregate quartz-feldspar.

*L-986:* Fordham gneiss. Collected on N. Y. Route 35, 0.7 mile north of Route 124—at north end of Ward Pound Ridge Reservation. This is a coarse-grained hornblende-biotite gneiss. The biotite is subordinate to hornblende and commonly has magnetite along cleavage planes. The separated biotite is very fresh in appearance, about 1 to 2 percent aggregate including hornblende.

*L-987:* Hornblende-pyroxene-plagioclase gneiss (Fordham gneiss). Collected on N. Y. Route 22 at intersection of Route 120 at northern end of Kensico Reservoir. The separated hornblende is black in appearance with only a trace of impurities—no biotite.

*L-988:* Quartz-plagioclase-biotite gneiss. Collected on Route 35, 0.3 mile east of junction with Route 123 (on N. Y.-Conn. boundary at Greenwich). About 2 percent aggregate in separated biotite, which is unaltered in appearance. No visible chlorite.

*L-989:* Granitic gneiss. Collected on State Highway 123, 3 miles east of Pound Ridge, N. Y. New road cut. Rusty weathered gneiss. The reddish biotite is locally altered to chlorite and magnetite and is intergrown with muscovite. About 5 percent chlorite and 5 percent aggregate in separated biotite.

*L-990:* Biotite-muscovite-garnet schist. Collected on Connecticut Route 123 (New Canaan) 0.4 mile north of Merritt Parkway. This is a medium-grained, weathered schist. Separated biotite has about 5 percent chlorite. 2 percent aggregate quartz and feldspar. Biotite appears slightly altered.

*L-991:* Granitic gneiss. Collected on U. S. Route 7, Wilton, Conn. The separated biotite appears moderately altered. Possibly 10 percent chlorite and about 3 percent aggregate quartz-feldspar.

*L-992:* Hornblende-biotite-feldspar gneiss. Collected on U. S. Route 7, 0.3 mile south of Route 102 intersection (Branchville, Conn.) About 3 percent aggregate in separated biotite with trace of hornblende. Biotite appears quite fresh.

*L-993:* Garnet-biotite-feldspar schist. Collected along U. S. Route 7, 5.5 miles north of sample location for L-992 (Manhattan formation). The biotite is locally altered to chlorite. Separated biotite has about 3 percent aggregate including muscovite.

*L-994:* Garnet-biotite-feldspar gneiss (Manahattan fm.). Collected west of Danbury, Conn. on Interstate 84, 2.0 miles east of the N. Y.-Conn. state line (on north side of highway). Separated biotite very fresh in appearance; no chlorite. Trace of aggregate.

*L-995:* Biotite-garnet-feldspar gneiss. Collected on south side of Interstate 84, 2.7 miles west of N. Y.-Conn. state line, Manhattan formation. Similar to L-994 but finer-grained, and the biotite is more ragged. Separated biotite has about 5 percent aggregate, chiefly quartz.

*L-996:* Biotite-garnet-sillimanite gneiss. 0.3 mile north of Conn. Route 33 on Ridgebury Road, Ridgefield, Conn. Essentially pure biotite separate with no chlorite and about 1 percent aggregate.

*L-997:* Biotite-pyroxene gneiss (Fordham gneiss). Sample collected on Danbury's southern town limits, on Southern Blvd. Magnetite is pseudomorphic after biotite and occurs along biotite-diopside foliation planes. Separated biotite appears quite fresh. No chlorite. About 1 percent aggregate.

*L-998:* Muscovite-biotite schist. Collected on Route 58, 1.7 miles south from U. S. Route 202 (Bethel, Conn.). Rather deeply weathered schist. Chlorite is a minor constituent along cleavage planes of biotite. Separated biotite appears moderately altered in part. Trace of aggregate with minor chlorite.

*L-1001:* Plagioclase-hornblende-biotite gneiss. Collected along Connecticut Route 104, 0.8 mile north of Merritt Parkway. Separated green hornblende contains less than 1 percent biotite. The biotite separate appears unaltered; about 1 percent chlorite.

*L-1002:* Feldspathic mica quartzite. Collected along Upper Shad Road, 0.8 mile east of Long Ridge Road in New York (north of Stamford, Conn.). No visible chlorite in separated biotite; 2 percent aggregate with trace of muscovite. Biotite appears unaltered.

*L-1003:* Plagioclase-biotite-muscovite schist. Collected along Connecticut Route 25, 1.5 miles north of Merritt Parkway (Trumbull). Although outcrop is badly weathered, the biotite appears very fresh and unaltered in thin section. Separated biotite appears fresh and contains only a trace of aggregate.

*L-1004:* Plagioclase-biotite gneiss. Collected along Connecticut Route 25, 5.3 miles north of L-1003. Separated biotite appears unaltered with no visible chlorite; trace of aggregate.

*L-1005:* Augen gneiss. Collected along Connecticut Route 25, 7.0 miles north of sample location L-1004. Less than 1 percent aggregate in separated biotite and about 5 percent chlorite.

*L-1006:* Plagioclase-quartz-biotite gneiss. Collected along Connecticut Route 34, 5.0 miles south of Interstate 84 (Newtown). Separated biotite appears very fresh, possibly 1 percent aggregate. No visible chlorite.

*L-1008:* Biotite-garnet schist. Collected along Connecticut Route 8, 5.1 miles south of intersection with Route 34 at Derby. Medium-grained weathered schist with garnet porphyroblasts. Separated reddish biotite shows some altered grains. No visible chlorite; trace of aggregate.

*L-1009:* Augen gneiss. Collected on Connecticut Route 8, 1.2 miles north of exit to Route 34. (Ansonia). About 5 percent chlorite in separated biotite and about 2 percent quartz-feldspar grains. Biotite appears very fresh.

*L-1010:* Microline-quartz-biotite augen gneiss. Collected on Connecticut Route 8, 5.3 miles north of last station (L-1009), at Seymour. Separated biotite appears unaltered, with less than 2 percent aggregate; less than 2 percent chlorite.

*L-1011:* Biotite-chlorite-staurolite-muscovite schist. Collected along Connecticut Route 8, 4.8 miles north of station L-1010. This is a weathered schist with a porphyroblastic texture—the large staurolite porphyroblasts have nearly completely altered to mica and chlorite. Much of the biotite has altered to chlorite and magnetite. Separated biotite appears moderately altered. Contains about 10 percent chlorite.

*L-1012:* Feldspar-biotite gneiss (Fordham gneiss). Collected along railroad cut at Oscawana, N. Y. about 2000 feet north of railroad station and about 1 mile south of contact with Cortlandt complex. Separated biotite appears very fresh with about 3 percent chlorite and trace of quartz and feldspar.

*L-1088:* Amphibolite. Collected on Interstate 84 (Southbury, Conn.), 1 mile south of exit to Connecticut Route 172. Separated greenish hornblende essentially pure.

*L-1089:* Biotite-feldspar gneiss. Collected along U. S. Route 6, 1.8 miles south of Nonewaug River Bridge, Woodbury, Conn. The separated reddish biotite is about 98 percent pure with chlorite and aggregate.

*L-1090:* Nonewaug granite. Collected on Connecticut Route 61, 1.3 miles north of junction with Route 6 (Woodbury, Conn.). The separated, coarse biotite appears moderately altered. Aboute 1 percent aggregate. No visible chlorite. The separated muscovite has reddish iron oxide on some grains, chiefly along edges.

*L-1092:* "Gray granulite". At Waterville, Conn., on "old" Route 8, nearly opposite Chase Brass. Separated biotite appears very fresh; traces of aggregate; no chlorite visible.

*L-1096:* Reynolds Bridge gneiss. Collected from new roadcut on Connecticut Route 8 at Reynolds Bridge, 0.25 mile south of intersection with Route 109. Two samples collected: a hornblende gneiss phase and a biotite-feldspar gneiss phase. Separated hornblende is essentially pure with trace of aggregate. The biotite fraction is essentially pure.

*L-1098:* "Gray granulite". Collected from roadcut on dirt road on west side of Pitch Reservoir, 1.2 miles east of East Morris, Conn. Separated biotite is better than 98 percent pure; no chlorite visible.

*L-1099:* Amphibolite. Sample from new roadcut on Connecticut Route 8, 2 miles south of Torrington and 0.25 mile north of intersection to Connecticut Route 4. Pure hornblende separate.

*L-1100:* Biotite-muscovite-garnet schist. Sample from deeply weathered roadcut on Conn. Route 4, 1 mile west of Burlington. Nearly pure biotite separate, trace of muscovite.

*L-1101:* Collinsville gneiss. Roadcut on Connecticut Route 4, 0.6 mile east of Farmington town line. Separated biotite is unaltered in appearance and contains 2 percent amphibole.

An undeformed, crosscutting pegmatite also sampled for book muscovite at this location. The muscovite analyzed contained no visible aggregate and 1 percent biotite.

*L-1102:* Amphibolite. Outcrop on Connecticut Route 72 at railroad crossing at western town limits of Bristol. Essentially pure hornblende separate.

*L-1103:* Biotite-muscovite-chlorite schist. Collected along Connecticut Route 47 at Roxbury town line, 3 miles south of Washington Depot. Separated biotite appears moderately altered. About 3 percent chlorite with aggregate.

*L-1104(a):* Plagioclase-biotite schist. Collected along Connecticut Route 47, 1.5 miles north of Washington Depot. Essentially pure biotite separate.

*L-1104(b):* Amphibolite. Collected along Connecticut Route 47, 2.1 miles north of Washington Depot. Hornblende separate is pure.

*L-1105:* Roxbury granite gneiss. Outcrop on Connecticut Route 67, 0.4 mile east of Bridgewater. Biotite separate about 98 percent pure, with muscovite and aggregate.

*L-1106:* Quartz-biotite gneiss. Outcrop of gray gneiss on Connecticut Route 133, 0.2 mile west of Housatonic River (Brookfield); about 1 percent chlorite with aggregate in separated biotite.

*L-1107:* Brookfield diorite gneiss. Sample from roadcut along entrance to Interstate 84, entering from Connecticut Route 25 at Hawleyville; pure biotite separate.

*L-1108:* Fordham gneiss. Outcrop at junction of Routes 124 and 116 (N.Y.) at North Salem near east end of Titicus Reservoir. Nearly pure biotite separate; minor aggregate.

*L-1109:* Waterbury formation. Collected at entrance to ramp to Interstate 84, entering from Connecticut Route 63. The separated biotite is about 95 percent pure, with chlorite and minor aggregate; appears moderately altered.

*L-1110:* Yonkers granitic gneiss (sample collected by Dr. L. Hall). Sample from Lake St. quarry (Westchester County, N.Y.) just south of intersection of Lake St. and Barnes Rd. About 2 percent biotite in separated hornblende.

*L-1127 to L-1137; and 1109:* These samples involved in the Rb-Sr investigation of the Waterbury dome were collected from one restricted locality on entrance to Interstate 84 from Connecticut Route 63, just west of Waterbury, Conn., and are from the Waterbury formation (paragneiss) forming the core of the Waterbury gneiss dome. This locality has been described by Gates and Martin (1967). Migmatite samples are included.

*L-1138:* Quartz-feldspar porphyry. Outcrop is located about 1000 feet west of Connecticut Route 8 and just south of Merritt Parkway between Interchanges 51 and 52. The outcrop is roughly circular in plan and quite restricted in areal extent, being less than 100 feet in diameter. The rock is massive and consists of phenocrysts of anhedral quartz, subhedral to euhedral albite and microcline and ragged biotite. Muscovite is subordinate to biotite. Fine-grained quartz-feldspar groundmass. Quartz shows evidence of strain. Phenocrysts compose about 40 percent of rock. Estimated mode (percent): Quartz, 45; plagioclase, 20; microcline, 30; biotite, 5; muscovite, 1. Accessory zircon and iron ore with some fluorite.

TABLE 4
Rubidium—strontium results
Intrusive porphyry

| Sample | Rb(ppm) | Sr(ppm) | $Rb^{87}/Sr^{86}$ | $Sr^{87}/Sr^{86}$ Calculated | $Sr^{87}/Sr^{86}$ Normalized |
|---|---|---|---|---|---|
| L-1138 | 294.6 | 501.2 | 1.70 | 0.7127 | 0.7128 |
| | 299.3 | 499.7 | 1.73 | 0.7118 | 0.7133 |
| L–1138 Plagioclase and quartz (fine fraction) | 97.28 | 396.9 | 0.708 | 0.7089 | 0.7089 |
| | 86.25 | 346.7 | 0.719 | 0.7084 | 0.7088 |
| L–1138 Microcline | 603.1 | 779.6 | 2.24 | 0.7149 | 0.7149 |
| L–1138 Microcline (fine fraction) | 553.9 | 692.3 | 2.31 | 0.7153 | 0.7153 |
| L–1138 Biotite | 924.9 | 21.69 | 128.6 | 1.162 | 1.161 |
| | 964.7 | 21.87 | 133.1 | 1.159 | 1.159 |