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$^{40}Ar/^{39}Ar$ ages of detrital muscovite and whole-rock slate/phyllite, Narragansett Basin, RI-MA, USA: implications for rejuvenation during very low-grade metamorphism

R.D. Dallmeyer[1] **and A. Takasu**[2]

[1] Department of Geology, University of Georgia, Athens, GA 30602, USA
[2] Department of Geology, Shimane University, 690 Matsue, Japan

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Abstract. Late Pennsylvanian sedimentary rocks in the Narragansett basin were metamorphosed (lower anchizone to sillimanite grade) during late Paleozoic regional metamorphism at ca. 275–280 Ma. Twenty-five variably sized concentrates of detrital muscovite were prepared from samples collected within contrasting low-grade areas (diagenesis – lower greenschist facies). Microprobe analyses suggest that the constituent detrital grains are not chemically internally zoned; however, some grains within several concentrates display very narrow (<25 μm), compositionally distinct, low-grade, epitaxial peripheral overgrowths. Detrital muscovite concentrates from the lower anchizone are characterized by internally concordant $^{40}Ar/^{39}Ar$ age spectra which define plateau ages of ca. 350–360 Ma. These are interpreted to date post-Devonian (Acadian) cooling within proximal source areas. Concentrates from lower grade sectors of the middle anchizone display slightly discordant spectra in which apparent ages systematically increase from ca. 250–275 Ma to define intermediate- and high-temperature plateaus of ca. 360–400 Ma. Detrital muscovite within samples from higher grade sectors of the middle anchizone and the upper anchizone are characterized by systematic low age discordance throughout both low- and intermediate-temperature increments. High-temperature ages only range up to ca. 330 Ma. Six size fractions of detrital muscovite from a sample collected within the lower greenschist facies have similarly discordant spectra, in which, apparent ages increase slightly throughout the analyses from ca. 250 Ma to 275 Ma. The detrital muscovite results are interpreted to reflect variable affects of late Paleozoic regional metamorphism. However, it is uncertain to what extent the systematic low age spectra discordance reflects intracrystalline gradients in the concentration of ^{40}Ar and/or experimental evolution of gas from relatively non-retentive epitaxial overgrowths. However, low age discordance occurs regardless of the extent of epitaxial overgrowth. Intermediate-temperature increments evolved during $^{40}Ar/^{39}Ar$ whole-rock analyses of five slate/phyllite samples are characterized by internally consistent apparent K/Ca ratios. These are attributed to gas evolved from constituent, very fine-grained white mica. Samples from lower grade portions of the middle anchizone are characterized by intermediate-temperature apparent ages which systematically increase from ca. 275–300 Ma to ca. 360–375 Ma before evolution of a high-temperature contribution from detrital plagioclase feldspar. This age variation may reflect partial late Paleozoic rejuvenation of very fine-grained detrital material with a source age similar to that for the detrital muscovites. Slate/phyllite samples from upper sectors of the middle anchizone and from the upper anchizone were completely rejuvenated during late Paleozoic metamorphism and record intermediate- and high-temperature plateau ages of ca. 270–290 Ma. These data document that metamorphic conditions of the lower to middle biotite zone (ca. 325–350 °C) are required to completely rejuvenate intracrystalline argon systems of detrital muscovite. Therefore, the $^{40}Ar/^{39}Ar$ dating method may be useful in determination of detrital muscovite provenance and in resolution of the metamorphic evolution of low-grade terranes.

Offprint requests to: R.D. Dallmeyer

Introduction

Previous K-Ar and/or $^{40}Ar/^{39}Ar$ studies have demonstrated that argon loss may occur from clay minerals as a result of: (1) transformation of detrital $1M_d$ to authigenic $2M_1$ illite; (2) thermally induced volume diffusion; and/or, (3) recrystallization (e.g., Aronson and Hower 1976; Huziker et al. 1986; Reuter 1987). Although these processes occur in response to increasing temperature, the thermal conditions required to rejuvenate intracrystalline argon systems within detrital $2M_1$ illite have not been closely bracketed. A detailed $^{40}Ar/^{39}Ar$ dating program has been carried out on detrital muscovite and whole-rock slate/phyllite within the northwestern Narragansett Basin, Rhode Island and

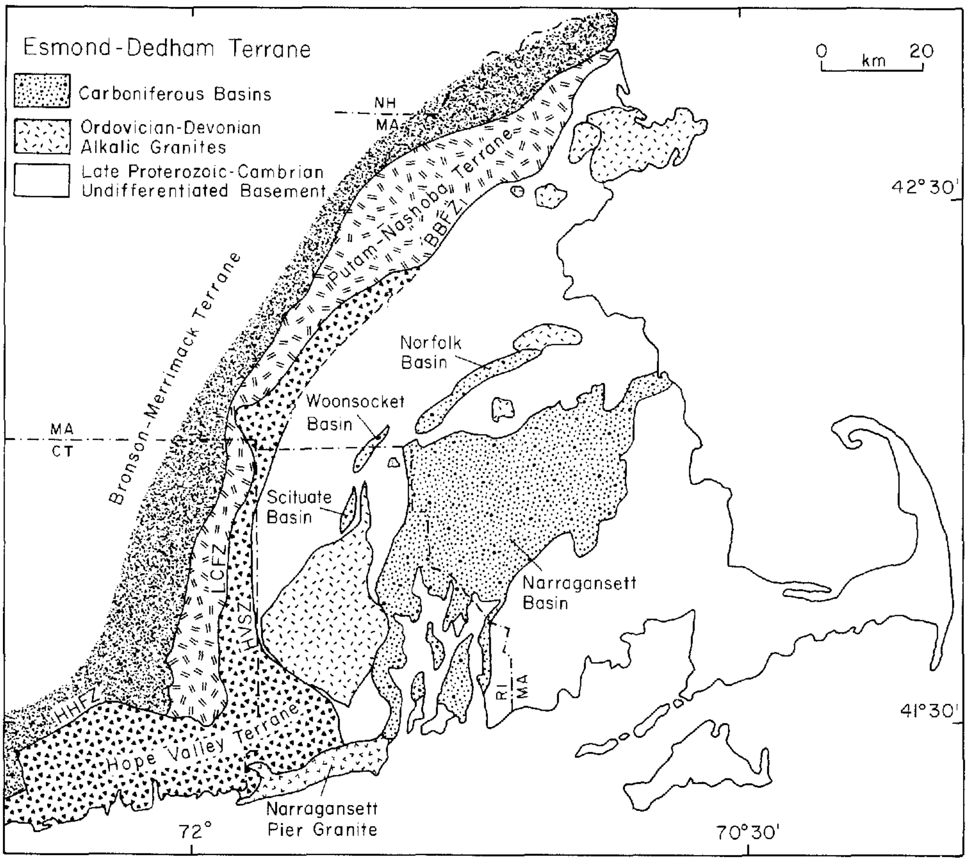

Fig. 1. Major lithotectonic elements of southeastern New England (compiled from Hermes and Zartman 1985; O'Hara and Gromet 1985; Gromet 1989): HHFZ – Honey Hill fault zone; LCFZ – Lake Char fault zone; BBFZ – Bloody Bluff fault zone; HVSZ – Hope Valley shear zone

Massachusetts (Fig. 1). The variably metamorphosed Pennsylvanian sedimentary rocks exposed within the basin provide a unique natural laboratory for study of isotopic rejuvenation because: (1) sedimentary age is well constrained and similar stratigraphic intervals may be sampled at various metamorphic grades (diagenesis to amphibolite facies); (2) previous geochronologic studies in high-grade areas have closely bracketed the timing of tectonothermal events; (3) previous regional studies of illite crystallinity have generally outlined the metamorphic character of the low-grade terrane; and, (4) it is possible to sample both metapelite and intercalated metasandstone with detrital muscovite (thereby providing a direct control on detrital ages).

Results of the $^{40}Ar/^{39}Ar$ analyses together with compositional characteristics of the detrital muscovite and matrix authigenic white-mica provide important constraints for both the mechanisms and conditions required for thermal rejuvenation of intracrystalline argon systems within $2M_1$ mica. These results provide significant new tools for use in evaluating the thermal evolution of sedimentary basins.

Geologic setting

Lithological characteristics

The geologic setting of the Narragansett Basin has been outlined by numerous workers, including Quinn (1971), Murray and Skehan (1979), Skehan et al. (1979), and Murray et al. (1981). The Basin contains a thick (ca. 7 km) clastic section of largely non-marine, fluviatile, coal-bearing metasedimentary rocks ranging up to late Pennsylvanian age (Westphalian B through Stephanian A or B; Lyons and Darrah 1978). These are in unconformable and fault contact with a crystalline basement comprised of late Proterozoic meta-igneous rocks and Cambrian metasedimentary units (Figs. 1 and 2). Mosher (1983) suggested that all of the Pennsylvanian rocks were proximally derived during formation of a series of intracratonic grabens.

Tectonothermal evolution

Northern segments of the Narragansett Basin have been deformed into open, gently plunging folds and record relatively low grades of regional metamorphism. Prograde isograds have been mapped in this area by Quinn (1971) and Murray et al. (1981). These include isograds based on the first appearance of chlorite, chloritoid, biotite, and garnet (Figs. 2 and 3). Wiechmann (1979) mapped the disappearance of detrital biotite in arkosic units (Fig. 3).

Hepburn and Rehmer (1981) reported preliminary illite crystallinity for sub-biotite grade portions of the Narragansett Basin and outlined three low-grade zones on the basis of half-height peak widths of the 10 Å reflection for bulk <2 µm size fractions isolated from slate/phyllite (Fig. 3). These included a diagenetic zone (>7.25 mm), an anchizone (7.25–4.6 mm), and a sub-biotite greenschist zone (<4.6 mm). They divided their anchizone into upper and lower segments along a boundary of 6.0 mm. They suggested that this marked the "... place at which chlorite growth is accelerated and unstable clastics replaced...", and suggested that it could be used as an approximate boundary for the chlorite isograd. The extensive area of diagenesis outlined by Hepburn and Rehmer (1981) is inconsistent with the singular occurrence of only $2M_1$

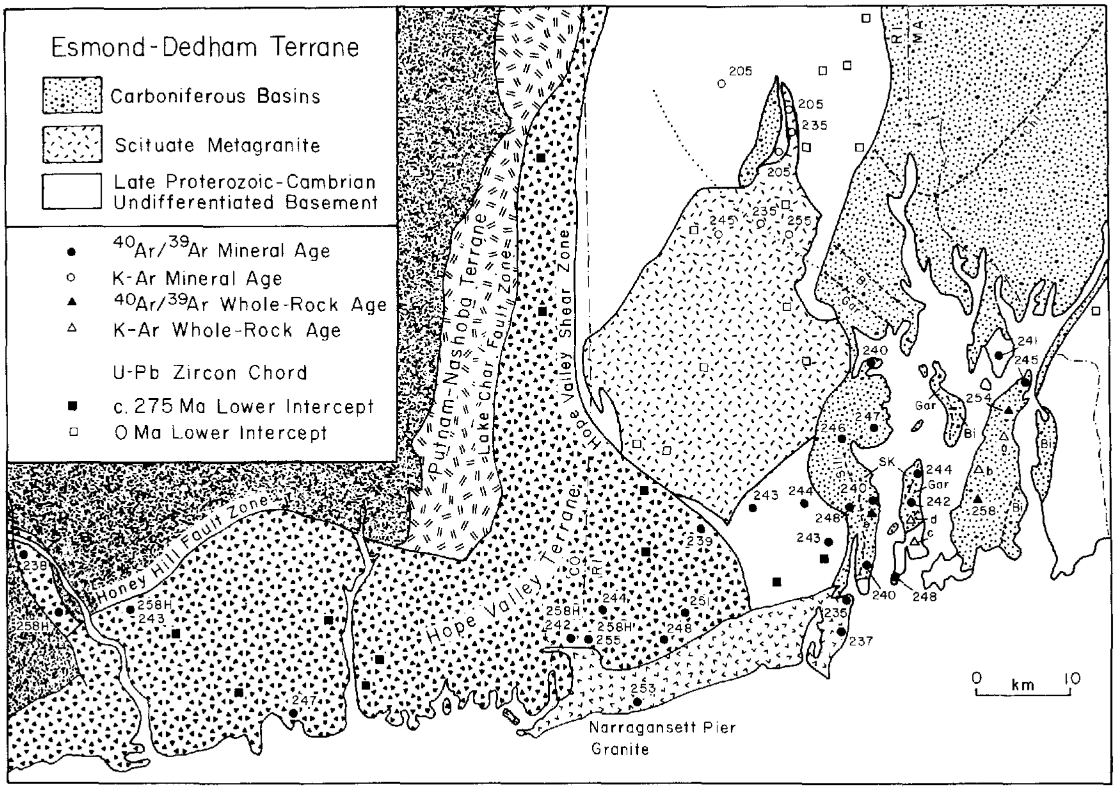

Fig. 2. Previously reported isotopic ages from the Narragansett Basin and late Proterozoic-Cambrian basement (Hope Valley and Esmond-Dedham terranes). Base map compiled from O'Hara and Gromet (1985), Hermes and Zartman (1985), and Gromet (1989). Metamorphic isograds within the Narragansett Basin modified from Murray and Skehan (1979) and Murray (1981). Projection of the garnet isograd northwestward from the Narragansett Basin from Day and Brown (1980). $^{40}Ar/^{39}Ar$ mineral ages (biotite except for hornblende, H) and whole-rock phyllite ages from Dallmeyer (1982; Rhode Island and eastern Connecticut) and Wintsch and Sutter (1986; central Connecticut). K-Ar ages from Zartman et al. (1970; northern Rhode Island) and Hurley et al. (1960; Narragansett Basin; a. 258 Ma, b. 235 Ma, d. 255 Ma, and e. 235 Ma). Locations where highly discordant U-Pb zircon analyses yielded lower concordia intercept dates of ca. 275 Ma are indicated (from Zartman and Naylor 1984; Hermes and Zartman 1985; Zartman, Hermes and Pease 1988). Also shown are the locations of samples which yielded less discordant U-Pb zircon analyses with lower concordia intercepts trending toward 0 Ma

white-mica polytypes and anthracite or meta-anthracite coal (Skehan et al. 1979; Murray et al. (1979); Murray and Raben 1980; Wintsch et al. 1980).

Previous geochronology

Fleming (1964) reported K-Ar ages for various size fractions of detrital muscovite separated from Pennsylvanian metasedimentary rocks within low-grade segments of the Narragansett Basin. From arkosic graywacke within the Dighton conglomerate he reported ages of 355 Ma (grains >0.25 mm) and 295 Ma (grains 0.11–0.18 mm). From a similar lithology within the Rhode Island formation he listed ages of 340 Ma (grains 0.32–0.42 mm) and 320 Ma (grains 0.25–0.32 mm). He interpreted these results to indicate a metamorphic detrital source of at least 355 Ma. Fleming suggested that late Paleozoic metamorphism effected partial argon loss from the smaller muscovite grains because they recorded younger K-Ar ages at both sites examined.

Hurley et al. (1960) reported K-Ar ages of 235 and 258 Ma for two whole-rock phyllite samples from southeastern, low-grade portions of the metamorphosed Pennsylvanian section (Fig. 2). Dallmeyer (1982) presented internally concordant $^{40}Ar/^{39}Ar$ release spectra for three whole-rock phyllite which corresponded to plateau ages of 250, 254, and 258 Ma (Fig. 2).

Kocis et al. (1978) reported U-Pb ages of 276 and 277 Ma for monazite concentrates from two samples of the Narragansett Pier granite which was emplaced following regional D_2 deformation. These are consistent with slightly discordant U-Pb zircon analyses that suggest a granite crystallization date of 272 ± 4 Ma (Hermes et al. 1981). This together with the metamorphic and structural continuity previously described for the Narragansett Basin (e.g., Murray and Skehan 1979), suggest that the tectonothermal chronology outlined for higher grade parts of the basin may also be applicable to the metamorphism and D_1 deformation recorded in lower grade areas. Following this chronology, the ca. 250–260 Ma K-Ar and $^{40}Ar/^{39}Ar$ plateau dates reported for whole-rock slate/phyllite samples from lower grade segments of the Narragansett Basin has been interpreted to date post-metamorphic cooling following attainment of maximum thermal conditions at ca. 275–280 Ma, and indicate complete rejuvenation of argon systems within all constituent detrital phases (Dallmeyer 1982). Additional regional geochronological controls are indicated in Fig. 2.

Analytical methods

Various size fractions of detrital muscovite have been separated from nine samples of metaconglomerate and metasandstone from the Rhode Island formation and the Dighton conglomerate collected within low-grade portions of the Narragansett Basin. Sample locations are indicated in Fig. 3 and coordinates are listed in the Appendix. Several representative slate/phyllite samples were also collected at each locality. These were crushed and sieved following

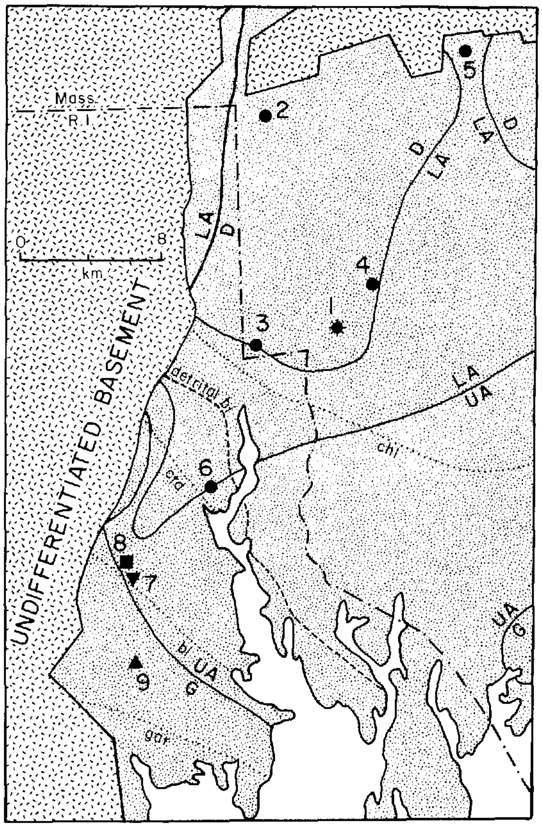

Fig. 3. Generalized geologic map of northwestern sectors of the Narragansett Basin (Rhode Island and Massachusetts) showing locations sampled for the present study (1–9). Low-grade metamorphic zonation reported by Hepburn and Rehmer (1981) is shown: *D*: diagenesis; *LA*: lower anchizone; *UP*: upper anchizone; *G*: lower greenschist. $^{40}Ar/^{39}Ar$ sample locations are ornamented to reflect quartz-normalized illite crystallinity determined in this study: ✸ diagenesis/lower anchizone, ● middle anchizone, ▼ upper anchizone, ■ upper anchizone/lower greenschist, ▲ lower greenschist. Prograde "isograds" compiled from Quinn (1971) and Murray et al. (1981): *chl*: chlorite; *ctd*: chloritoid; *bi*: biotite; *gar*: garnet. Disappearance of detrital biotite in arkosic metasedimentary units in the Narragansett Basin from Wiechman (1979)

removal of weathered surfaces with a wire brush and thorough washing. Illite crystallinity was determined on bulk <2 μm size-fractions isolated from 3 to 4 different slate/phyllite samples collected within each exposure. Five whole-rock slate/phyllite samples have been investigated using $^{40}Ar/^{39}Ar$ incremental-release techniques.

X-ray diffraction

Selected samples were prepared for determination of illite crystallinity by desegregation in a shatter box for 20 s Bulk <2 μm size-fractions were isolated by differential settling in Atterberg cylinders and centrifugation (following techniques listed in Reuter 1985). Illite crystallinity of the <2 μm size-fractions was determined from oriented sedimentation slides by comparison of the (001) illite and (100) quartz (internal standard) reflections following the methods of Weber (1972). Cross-calibration of 28 samples (correlation coefficient = 0.97) from Reuter (1985) suggests the following boundary values are appropriate for the equipment setting employed at the University of Georgia (compared with the calibrations of Teichmüller et al. 1979): greenschist/anchizone = 115; anchizone/diagenesis = ca. 350. In the present study boundaries between the upper anchizone/middle anchizone and middle anchizone/lower anchizone are defined by crystallinity values of 190 and 270 respectively. According to Kubler (1967) and Dunoyer de Segonzac (1969) minimum illite crystallinity values are reached within the epizone whereas Teichmüller et al. (1979) define the greenschist/anchizone boundary by the first appearance of minimum crystallinity values. As a result, rocks that suggest reflection of epizonal metamorphism according to Kubler (1967) and/or Dunoyer de Segonzac (1969) are classified as upper anchizone by Teichmüller et al. (1979).

Electron probe analysis

Representative grains within the dated detrital muscovite concentrates were analyzed in carbon-coated mounts with electron-probe microanalyzers at Shimane University and Kyoto University. In addition, both detrital and recrystallized matrix grains were analyzed *in situ* in carbon-coated, polished thin-sections. At Shimane University a wave-dispersive, JEOL JSM-733 probe was operated with 15.0 kV accelerating voltage and 20 nA specimen current. Correction procedures followed those of Bence and Albee (1968) and Yamaguchi et al. (1978). The microprobe at Kyoto University is a energy-dispersive system (Kevex Corporation EDS), attached to a Hitachi S-550 scanning electron microscope. Acceleration voltage and beam current were 15.0 kV and 0.3 nA, respectively. Analytical procedures generally followed those described in detail by Mori and Kanehira (1984).

$^{40}Ar/^{39}Ar$ analysis

The techniques used during $^{40}Ar/^{39}Ar$ analyses of whole-rock samples from the Narragansett Basin generally followed those described in detail by Dallmeyer and Keppie (1987) or Dallmeyer and Gil-Ibarguchi (1990). Whole-rock powders were wrapped in aluminum-foil packets, encapsulated in sealed quartz vials, and irradiated in either the US Geological Survey TRIGA reactor (samples 1, 2A, 3A, 5B, 6A, 6B, 7A, 8 and 9) or the H-5 position of the Ford Reactor at the University of Michigan (samples 2B, 4, 5A and 7B). Variations in the flux of neutrons along the length of the irradiation assembly were monitored by several mineral standards (including MMhb-1: Samson and Alexander 1987). Samples were incrementally heated until fusion. Measured isotopic ratios were corrected for total system blanks and the effects of mass discrimination. Interfering isotopes produced during irradiation were corrected using the factor reported by Dalrymple et al. (1981) for the TRIGA reactor or Harrison and FitzGerald (1986) for the Ford Reactor. Apparent $^{40}Ar/^{39}Ar$ ages were calculated from the corrected isotopic ratios using the decay constants and isotopic abundance ratios listed by Steiger and Jäger (1977). Intra-laboratory uncertainties are reported and have been calculated by statistical propagation of uncertainties associated with measurement of each isotopic ratio (at two standard deviations of the mean) through the age equation. Interlaboratory uncertainties are ca. ± 1.25–1.5% of the quoted age. Analysis of the MMhb-1 monitor indicates that apparent K/Ca ratios may be calculated through the relationship $0.518\ (\pm 0.005) \times {}^{39}Ar/{}^{37}Ar$ corrected (TRIGA reactor) or $0.505\ (\pm 0.003) \times {}^{39}Ar/{}^{37}Ar$ corrected (Ford Reactor).

Results

Illite crystallinity

Quartz normalized illite crystallinity values display little intrasample variation within the nine exposures examined in detail (Table 1). Averages at each location range between 239 and 100, and indicate metamorphic condi-

Table 1. Quartz-normalized illite crystallinity determinations on bulk < 2 µm size fractions from slate/phyllite at the locations sampled for $^{40}Ar/^{39}Ar$ dating in low-grade sectors of the Narragansett Basin

Location	Quartz-normalized illite crystallinity[a]	Suggested metamorphic grade
1	239	Diagenesis/lower anchizone
2	186	Middle anchizone
3	182	
4	159	
5	156	
6	154	
7	129	Upper anchizone
8	115	Upper anchizone/lower greenschist
9	100	Lower greenschist facies

[a] Comparison of (001) reflection in illite and (100) reflection in internal quartz standard (after Weber 1972)

tions varying between the diagenesis/lower anchizone transition (sample 1), the middle anchizone (samples 2–6), the upper anchizone (sample 7), the upper anchizone/lower greenschist transition (sample 8) and the lower greenschist facies (sample 9). Samples numbers have been assigned to reflect an increasing metamorphic grade based on the average illite crystallinity within each exposure.

Mineral chemistry

Representative grains within each concentrate and corresponding thin-section have similar chemical characteristics and display no internal chemical zonation (Tables 2 and 3[1]; Figs. 4 and 5). Detrital grains within samples 1, 3A, 4, 7A and 8 display wide ranges in chemical composition. Detrital muscovite grains from samples 2A, 5A, 6A and 9 display more limited ranges in composition (suggestive of more restricted source regions). Recrystallized matrix grains within samples from the middle anchizone (2A, 3A, 4, 5A and 6A) display a markedly different chemical trend (Table 4; Fig. 5) that is consistent with a very low-grade metamorphism (e.g., Enami 1983; Takasu and Dallmeyer 1990). Recrystallized matrix grains from the upper anchizone (samples 7A and 8) are characterized by higher mole fraction of paragonite, probably reflecting higher metamorphic temperatures. Matrix muscovite within sample 9 (lower greenschist facies) has a slightly lower paragonite component than the trend displayed by the middle anchizone samples.

Some detrital grains within samples 3A, 4, 5A and 9 have a thin marginal rim (up to 20 µm wide) with a chemical composition distinct from interior regions and comparable to the recrystallized matrix (Table 4;

[1] Tables 2–5 are on file and may be obtained at no charge from the first author.

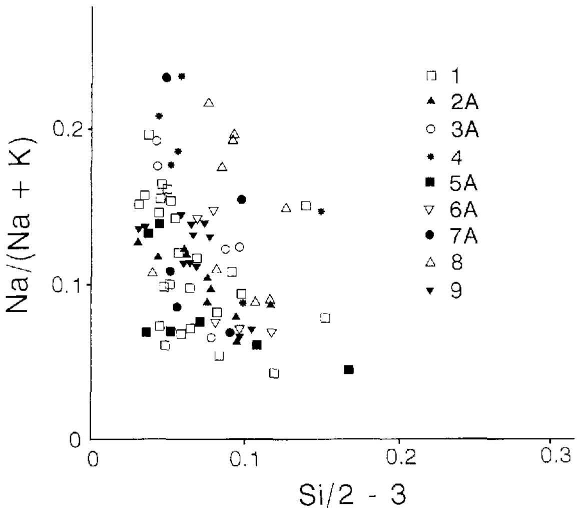

Fig. 4. Compositions of interior portions of representative grains within detrital muscovite concentrates expressed in terms of celadonite component in muscovite (atomic Si/2–3) and paragonite/muscovite ratio (atomic Na/Na+K). *Si*: silicon atoms per 24 oxygen atoms

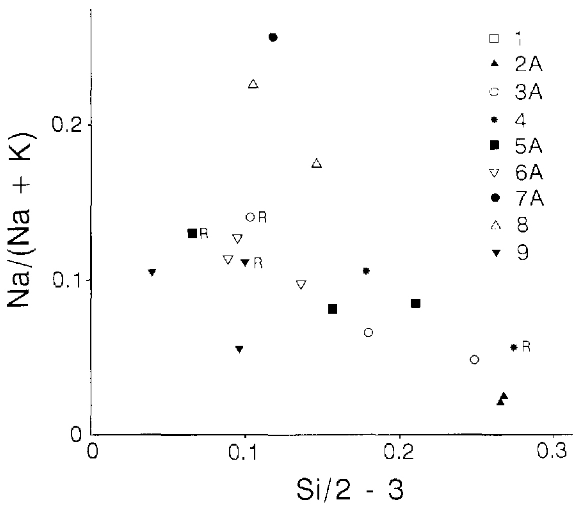

Fig. 5. Compositions of very fine-grained, recrystallized matrix muscovite and epitaxial rim overgrowths on detrital grains (*R*) measured in situ. Data plotted as in Fig. 4

Fig. 5). These are interpreted as reflecting epitaxial metamorphic overgrowths. Some of the recrystallized matrix grains and detrital rims have a larger celadonite component than the detrital interiors. This suggests that either a higher pressure and/or a lower temperature was maintained during matrix recrystallization compared to that which characterized the original source region.

$^{40}Ar/^{39}Ar$ ages

Twenty-five variably sized concentrates of detrital muscovite and 5 whole-rock samples have been analyzed from the Narragansett Basin. The $^{40}Ar/^{39}Ar$ data are

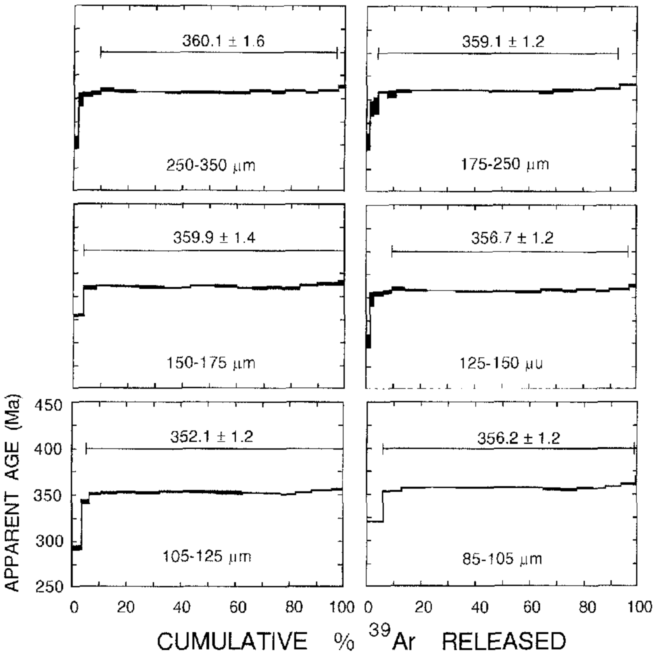

Fig. 6. $^{40}Ar/^{39}Ar$ apparent age spectra of various size-fractions of detrital muscovite concentrates from metasandstone of the Dighton conglomerate collected within the diagenesis/lower anchizone (location 1) in the Narragansett Basin. Analytical uncertainties (two sigma intra-laboratory) are represented by the *vertical width* of bars. Experimental temperatures increase from *left* to *right*. Plateau increments and ages indicated

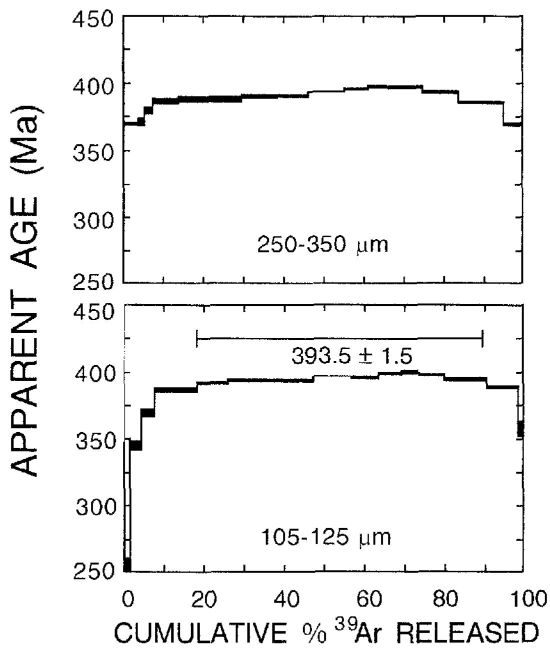

Fig. 7. $^{40}Ar/^{39}Ar$ apparent age spectra of two size-fractions of detrital muscovite concentrated from metasandstone of the Rhode Island formation collected within lower sectors of the middle anchizone (location 2) in the Narragansett Basin. Data plotted as in Fig. 6

listed in Tables 4 and 5 and are portrayed as age spectra in Figs. 6–15. Apparent K/Ca ratios recorded by increments evolved from the muscovite concentrates are very large with considerable associated uncertainties. They do not display any significant and/or systematic intrasample variations which suggests that experimental evolution of gas occurred from compositionally uniform populations of intracrystalline sites.

Diagenesis/lower anchizone transition

Six size-fractions of detrital muscovite have been analyzed from a sample of metaconglomerate collected within the Dighton conglomerate at location 1. These display internally concordant apparent age spectra (Fig. 6) with plateau ages ranging between 360.1 ± 1.6 Ma (250–350 μm) to 352.1 ± 1.2 Ma (105–125 μm). The plateau ages are considered geologically significant, and are interpreted to date cooling through the closure temperatures within the source terrane of the detrital grains. Although not calibrated experimentally, using the preliminary data of Robbins (1972) in the diffusion equations of Dodson (1973, 1979) suggests closure temperatures of 375 ± 25 °C are appropriate for argon retention in muscovite.

Middle anchizone

Location 2

Two size-fractions of detrital muscovite have been analyzed from a sample of metasandstone collected within the Rhode Island formation at location 2. These display internally discordant apparent age spectra (Fig. 7) corresponding to total-gas ages of 387.9 ± 1.7 Ma (250–350 μm) and 387.5 ± 2.0 Ma (105–125 μm). Nine intermediate-temperature increments evolved from the 105–125 μm size fraction record similar apparent ages corresponding to a plateau of 393.9 ± 1.5 Ma. This is interpreted as dating the last cooling through argon closure temperatures in the source region. The 105–125 μm size-fraction displays significant discordance in low-temperature increments which record systematically increasing apparent ages.

An internally discordant $^{40}Ar/^{39}Ar$ apparent age spectrum is displayed by a whole-rock sample of slate/phyllite collected at location 2 (Fig. 8). Except for the lowest temperature increment, all low- and intermediate-temperature increments are characterized by generally similar apparent K/Ca ratios which are attributed to gas evolution from very fine-grained white mica. Apparent ages systematically increase in the three low-temperature increments to ages of ca. 360 Ma recorded in intermediate-temperature portions of the experiment. Gas fractions evolved during high-temperature portions of

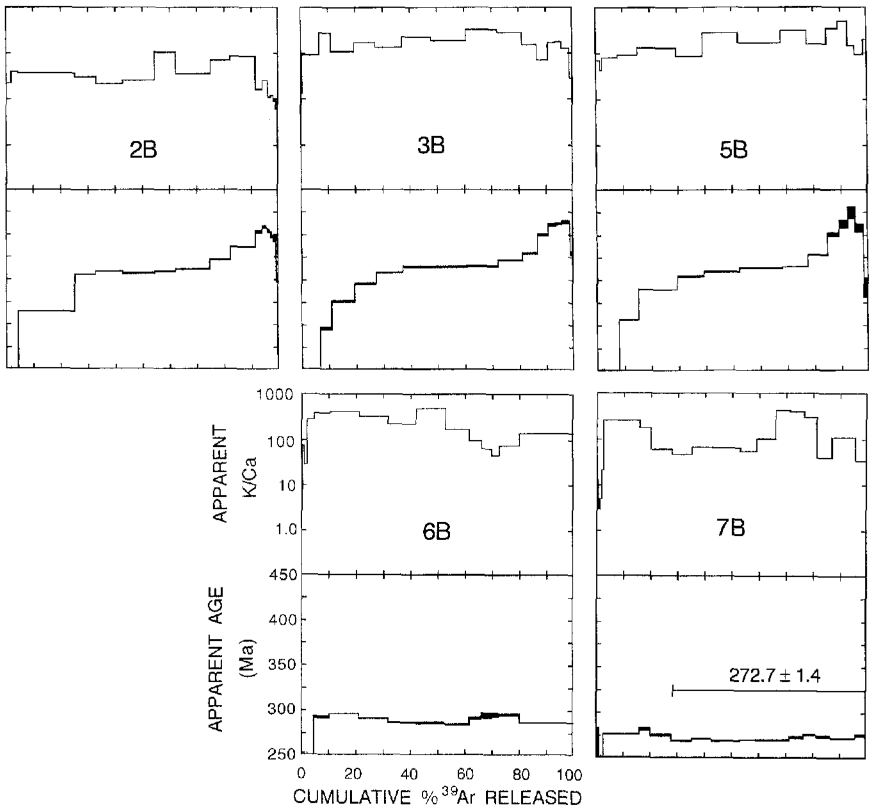

Fig. 8. $^{40}Ar/^{39}Ar$ apparent age and apparent K/Ca spectra of a whole-rock analyses of slate/phyllite collected at locations 2, 3, 5, 6 and 7. Data plotted as in Fig. 6. All spectra have the *coordinates indicated* for sample 6B

the analysis record increasing apparent ages and markedly decreasing apparent K/Ca ratios. This indicates partial evolution of gas from a relatively retentive phase with a low K/Ca ratio. Mineralogical characteristics suggest this was detrital plagioclase feldspar. The systematically increasing apparent ages recorded in intermediate-temperature portions of the analysis are interpreted as relating to gas evolved from very fine-grained white-mica.

Location 3

Three size-fractions of detrital muscovite have been analyzed from a sample of metasandstone collected from the Rhode Island formation at location 3. The three size-fractions display internally discordant apparent age spectra with slightly different characteristics (Fig. 9). The 250–350 μm size fraction displays systematically increasing apparent ages in the four low-temperature increments. The remaining 11 intermediate- and high-temperature gas fractions record similar apparent ages corresponding to a plateau of 385.2 ± 1.4 Ma. This is interpreted to date original cooling through argon retention temperatures in the source region. The 175–250 μm and 125–150 μm size fractions display more extensive low-temperature age discordance. Intermediate- and high-temperature increments record apparent ages in the range of 395–405 Ma but do not define plateaus.

A whole-rock slate sample from location 3 displays internally discordant apparent age and apparent K/Ca spectra (Fig. 8) with characteristics similar to that of slate from location 2. An exception is that a greater percentage of the low- and initial intermediate-temperature increments record systematically increasing apparent ages.

Location 4

Two size-fractions of detrital muscovite from metasandstone, collected at location 4 in the Rhode Island formation, display similarly discordant apparent age spectra (Fig. 10). Low- and initial intermediate-temperature increments record systematically increasing apparent ages whereas remaining intermediate- and high-temperature gas fractions record mutually similar plateau ages of ca. 360 Ma.

Location 5

Two concentrates of detrital muscovite have been analyzed from location 5. These display internally discordant age spectra (Fig. 11) in which apparent ages increase markedly and systematically throughout low-temperature portions of both analyses. In the 85–105 μm size fraction apparent ages increase systematically but less significantly in the intermediate-temperature increments, ranging between ca. 400 Ma and 410 Ma. In the 150–175 μm size fraction intermediate-temperature apparent ages increase from ca. 410 Ma to 420 Ma.

A whole-rock slate sample from location 5 is characterized by internally discordant apparent age and apparent K/Ca spectra which are generally similar to those displayed by samples 2B and 3B (Fig. 8).

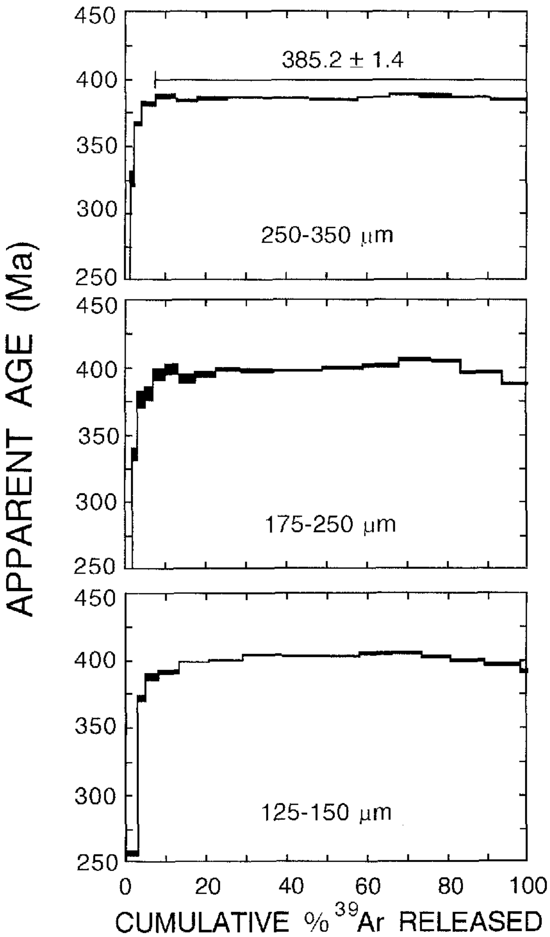

Fig. 9. $^{40}Ar/^{39}Ar$ apparent age spectra of various size-fractions of detrital muscovite concentrated from metasandstone of the Rhode Island Formation collected within lower sectors of the middle anchizone (location 3) in the Narragansett Basin. Data plotted as in Fig. 6

Location 6

A 175–250 µm size fraction of detrital muscovite was separated from metasandstone collected in the Rhode Island formation at location 6. This displays an internally discordant apparent age spectrum (Fig. 12) in which low- and initial intermediate-temperature gas fractions record systematically increasing ages. The remaining intermediate- and high-temperature increments yield a plateau of 385 Ma.

Whole-rock slate from location 6 displays an internally discordant spectrum (Fig. 8) in which most apparent ages range between ca. 290 Ma and 300 Ma.

Upper anchizone

Two size-fractions of detrital muscovite were separated from a sample of metasandstone collected within the Rhode Island formation at location 7. These display markedly discordant spectra (Fig. 13) in which apparent ages increase systematically throughout most low- and intermediate-temperature increments. Apparent ages recorded in high-temperature increments range between ca. 350–360 Ma (250–350 µm) and ca. 330–340 Ma (85–105 µm).

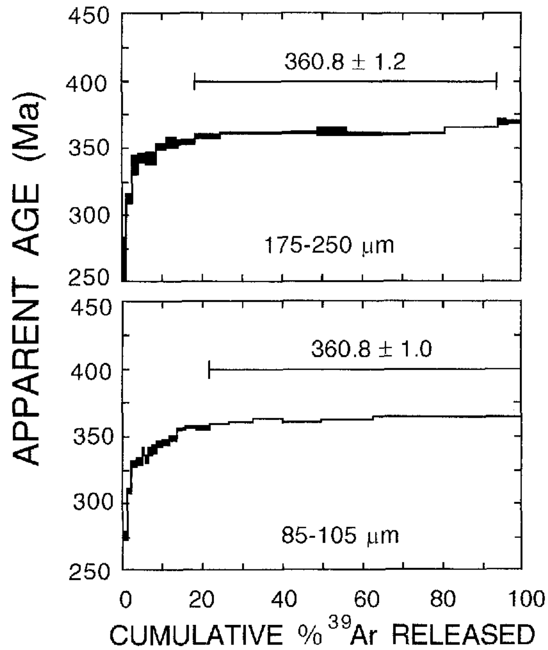

Fig. 10. $^{40}Ar/^{39}Ar$ apparent age spectra of two size-fractions of detrital muscovite concentrated from a metasandstone of the Rhode Island formation collected within central sectors of the middle anchizone (location 4) in the Narragansett Basin. Data plotted as in Fig. 6

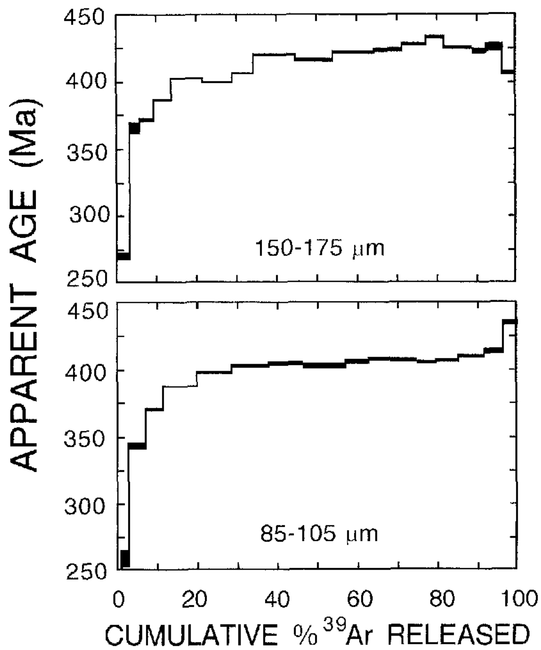

Fig. 11. $^{40}Ar/^{39}Ar$ apparent age spectra of two size-fractions of detrital muscovite concentrated from metasandstone of the Rhode Island formation collected within upper sectors of the middle anchizone (location 5) in the Narragansett Basin. Data plotted as in Fig. 6

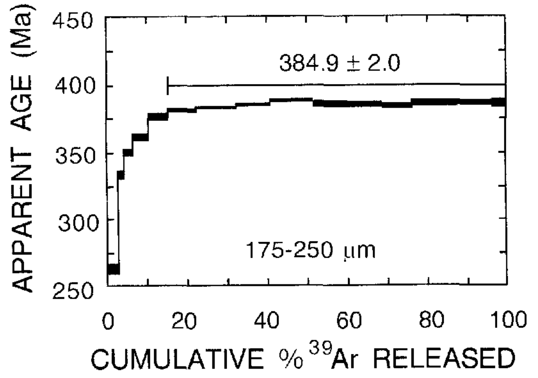

Fig. 12. $^{40}Ar/^{39}Ar$ apparent age spectrum of the 174–250 µm size-fraction of detrital muscovite concentrated from metasandstone of the Rhode Island formation collected within upper sectors of the middle anchizone (location 6) in the Narragansett Basin. Data plotted as in Fig. 6

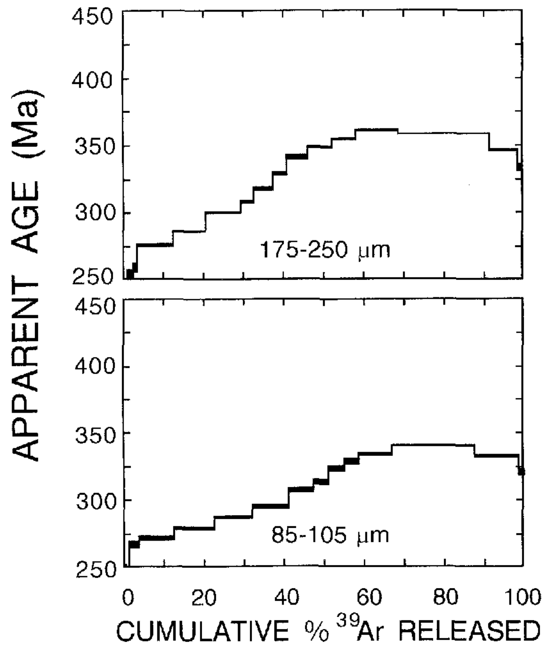

Fig. 13. $^{40}Ar/^{39}Ar$ apparent age spectrum of two size-fractions of detrital muscovite concentrated from metasandstone of the Rhode Island formation collected within the upper anchizone (location 7) in the Narragansett Basin. Data plotted as in Fig. 6

Whole-rock slate/phyllite from location 7 is characterized by a slightly discordant apparent age spectrum (Fig. 8) in which intermediate- and high-temperature gas fractions record similar apparent ages corresponding to a plateau of 273 Ma. This is interpreted to reflect complete rejuvenation of all constituent minerals (including detrital plagioclase) during late Paleozoic metamorphism at ca. 270–280 Ma.

Upper anchizone/lower greenschist transition

Both 250–350 µm and a 75–85 µm size fractions of detrital muscovite were concentrated from a sample of meta-

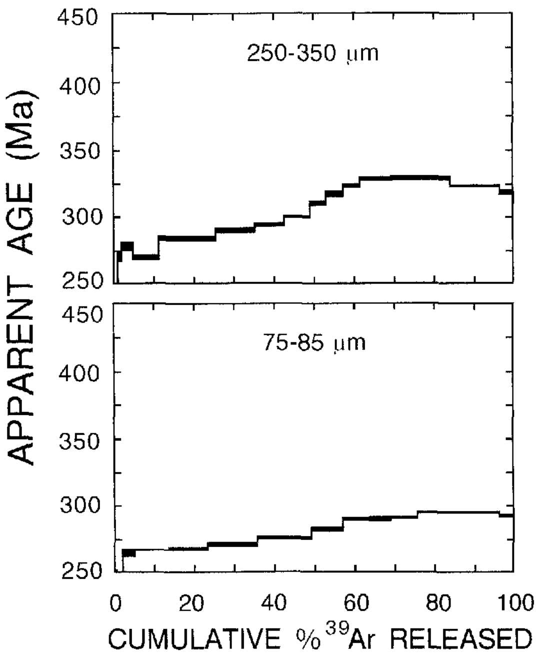

Fig. 14. $^{40}Ar/^{39}Ar$ apparent age spectra of two size-fractions of detrital muscovite concentrated from metasandstone of the Rhode Island formation collected within the upper anchizone/greenschist transition zone (location 8) in the Narragansett Basin. Data plotted as in Fig. 6

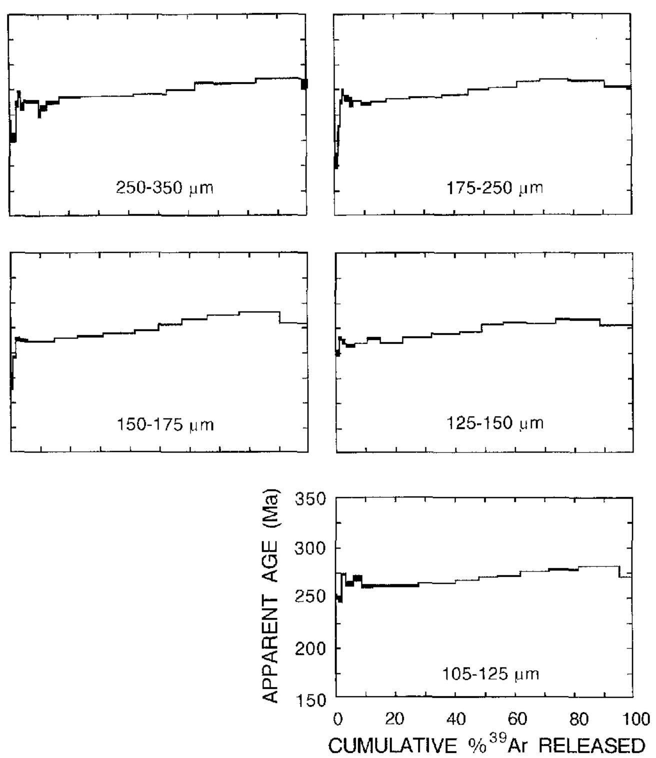

Fig. 15. $^{40}Ar/^{39}Ar$ apparent age spectra of several size-fractions of detrital muscovite concentrated from metasandstone of the Rhode Island formation collected within the lower greenschist facies (location 9) in the Narragansett Basin. Data plotted as in Fig. 6

sandstone collected at location 8. These are characterized by internally discordant spectra (Fig. 14). Low-temperature fractions evolved from the 250–350 μm size fraction record apparent ages of ca. 270–280 Ma. Most intermediate-temperature fractions record ages which increase systematically up to ca. 320–330 Ma. In the 75–85 μm size fraction ca. 270–280 Ma ages are recorded throughout both low- and most intermediate-temperature gas fractions. Apparent ages increase slightly up to ca. 280–290 Ma in high-temperature segments of the analysis.

Lower greenschist

Five size fractions of detrital muscovite were prepared from a sample of metasandstone collected within the Rhode Island formation at location 9. All display internally discordant apparent age spectra (Fig. 15) with generally similar characteristics. Apparent ages of ca. 270–280 Ma are recorded in most low- and initial intermediate-temperature increments. Apparent ages increase slightly in the remaining intermediate- and high-temperature gas fractions.

Interpretation

Detrital muscovite

The detrital muscovite concentrates display variable rejuvenation as a result of late Paleozoic metamorphism at ca. 275–280 Ma. All size-fractions from the lowest grade sample examined (location 1: diagenesis/lower anchizone transition) record well-defined plateau ages of ca. 355–360 Ma which are interpreted to date either post-metamorphic and/or post-magmatic cooling in the source region. This age range is comparable with K-Ar, $^{40}Ar/^{39}Ar$ and Rb-Sr mineral dates reported from surrounding basement regions in southeastern New England affected by Devonian (Acadian) metamorphism (e.g., Lyons and Livingston 1977; Robinson 1979; Ashwal et al. 1979; Zartman and Naylor 1984; Osberg et al. 1989).

Detrital muscovite concentrates from samples in the middle anchizone record distinct effects of late Paleozoic metamorphism. Intermediate- and high-temperature increments evolved from the 5 locations examined (2, 3, 4, 5 and 6) preserve intermediate- and high-temperature apparent ages in the range of ca. 360–400 Ma. These are interpreted to date cooling in the source area. The ca. 360–400 Ma age variation may reflect late Paleozoic exhumation and erosion of different crustal levels which had cooled through argon closure temperatures at different times following Acadian metamorphism. The various detrital muscovite size fractions from the middle anchizone record low-temperature apparent ages which systematically increase from ca. 250–275 Ma. This type of spectral discordance is similar to that predicted by Turner (1968) to result from partial, intracrystalline loss of radiogenic ^{40}Ar during superimposed thermal events. This behavior has been documented by thermally overprinted muscovite in several polymetamorphic terranes (e.g., Snee et al. 1988; Dallmeyer and Lécorché 1989). However, in the present setting some detrital grains in samples 3 A, 4 and 5 A display low-grade, epitaxial metamorphic overgrowths. It is therefore uncertain the extent to which the low-temperature age variations reflect intracrystalline gradients in the concentration of ^{40}Ar or experimental evolution of gas from relatively non-retentive epitaxial overgrowths. However, the low-temperature age variations are displayed by all of the detrital muscovite concentrates analyzed from the middle anchizone regardless of the presence of epitaxial overgrowths.

Detrital muscovite concentrates from the upper anchizone (locations 7 and 8) display more extensive late Paleozoic metamorphic overprinting. Apparent ages increase from ca. 250–275 Ma throughout both low- and most intermediate-temperature increments in all size fractions. High-temperature increments record maximum ages of 350–325 Ma (7A) and 280–325 Ma (8). In both samples the smaller size fraction displays more extensive late Paleozoic overprinting. No epitaxial overgrowths were detected in any of the detrital muscovite grains within the four size-fractions analyzed from the two upper anchizone samples. Therefore, the observed variations in apparent $^{40}Ar/^{39}Ar$ ages probably reflect intracrystalline gradients in the concentration of ^{40}Ar.

All gas fractions evolved from the five size-fractions of detrital muscovite from the highest grade sample analyzed (9; lower greenschist facies) record apparent $^{40}Ar/^{39}Ar$ ages ranging between ca. 250 and 275 Ma; however, apparent ages consistently increase slightly throughout the five analyses and plateaus are not defined. This suggests that late Paleozoic metamorphic conditions were not sufficient to totally rejuvenate the detrital grains.

Whole-rock slate/phyllite

Intermediate-temperature increments from the 5 whole-rock slate/phyllite samples examined are interpreted to largely relate to gas experimentally evolved from very fine-grained white mica. Samples from lower portions of the middle anchizone (2 B, 3 B, and 5 B) are characterized by intermediate-temperature apparent ages which systematically increase from ca. 275–300 Ma to ca. 360–375 Ma before a high-temperature contribution from detrital feldspar. This intermediate-temperature age variation may reflect partial late Paleozoic rejuvenation of very fine-grained detrital material of similar age to the coarser-grained detrital muscovite. Such patterns of spectral discordance have been documented for thermally overprinted whole-rock slate/phyllite in several other polymetamorphic terranes (e.g., Dallmeyer et al. 1988). Samples 6 B (upper sector of the middle anchizone) and 7 B (upper anchizone) were completely rejuvenated during late Paleozoic metamorphism, and record intermediate- and high-temperature apparent ages of ca. 270–290 Ma. It is interesting that although the whole-rock slate from location 6 was completely rejuvenated at ca.

275–280 Ma, detrital muscovite at that location displays relatively minor late Paleozoic rejuvenation.

Implications

Evaluating the implications of the $^{40}Ar/^{39}Ar$ results is complicated because of uncertainties in both duration and physical conditions of late Paleozoic metamorphism in low-grade sectors of the Narragansett Basin. On the basis of work in the Alps, Frey et al. (1980) estimated that temperatures of ca. 200–270 °C are likely attained in the anchizone. On the other hand, Teichmüller et al. (1979) indicated that temperatures of ca. 350 °C mark the anchizone/greenschist facies boundary. In the Narragansett Basin, Wiechmann (1979) and Wintsch et al. (1981) indicated that disappearance of detrital biotite in arkosic metasandstone (Fig. 3) may correspond to a temperature of ca. 200 °C. They suggested that the prograde biotite isograd may correspond to ca. 325 °C. If appropriate, these estimates indicate that conditions between ca. 200 °C and 325 °C may have characterized the late Paleozoic middle anchizone.

Frank and Stettler (1979) reported K-Ar and $^{40}Ar/^{39}Ar$ isotopic data for <2 μm size fractions from slate/phyllite samples collected along a profile of increasing regional metamorphism. Reasonably concordant $^{40}Ar/^{39}Ar$ age spectra were displayed by size-fractions isolated from samples collected at grades characterized by metamorphic temperatures of ca. 400 °C. The appearance of internally concordant spectra was coincident with the total transformation of $1M_d$ to $2M_1$ illite polytype. This suggests that what was termed "rejuvenation" by Frank and Stettler may reflect resetting of argon systems by intracrystalline restructuring of detrital $1M_d$ illites (e.g., Hunziker et al. 1986). The present $^{40}Ar/^{39}Ar$ results from the Narragansett Basin indicate that total rejuvenation of constituent $2M_d$ white mica in whole-rock slate/phyllite samples occurred in uppermost sectors of the middle anchizone which likely experienced metamorphic temperatures significantly <ca. 325 °C.

Snee et al. (1988) suggested that temperatures of ca. 270–285 °C effected a minor rejuvenation of muscovite (<ca. 15%) similar to that displayed by samples 2A and 3A from lower sectors of the middle anchizone in the Narragansett Basin. A generally similar temperature estimate is probably appropriate for the late Paleozoic metamorphic conditions maintained in the region of locations 2 and 3. The internally discordant $^{40}Ar/^{39}Ar$ age spectra displayed by all size-fractions of detrital muscovite in sample 9 (lowermost greenschist facies) suggest that temperatures in excess of ca. 325 °C may have been required to completely rejuvenate coarser-grained detrital muscovite (at least >ca. 100 μm).

Results presented herein suggest that the $^{40}Ar/^{39}Ar$ dating method can aid in evaluation of provenance for clastic sedimentary rocks. It is also useful in resolution of low grade metamorphic temperatures attained within clastic sedimentary successions.

Appendix

Sample locations

Location 1: Dighton Conglomerate, Attleboro 7 1/2′ Quad., Mass.: 41°55′56″N, 71°19′14″W: Northbound lane, I-95 at intersection with Rt. 123
Location 2: Rhode Island Fm., Wrentham 7 1/2′ Quad., Mass.: 41°23′20″N, 71°20′45″W: Masslight Quarry, Plainville, Mass
Location 3: Rhode Island Fm., Providence 7 1/2′ Quad., Mass.: 41°52′20″N, 71°22′57″W: northbound lane of I-95 at Slater Hill Rd. intersection
Location 4: Rhode Island Fm., Attleboro 7 1/2′ Quad., Mass.: 41°55′54″N, 71°17′31″W: railroad crossing at Thatcher Street; stop 5, Cameron (1979)
Location 5: Rhode Island Fm., Mansfield 7 1/2′ Quad., Mass.: 42°02′46″N, 71°14′24″W: I-95 cloverleaf at Rt. 140; stop 2, Hepburn and Rehmer (1981)
Location 6: Rhode Island Fm., Providence 7 1/2′ Quad., R.I.: 41°50′06″N, 71°24′09″W: University Heights Shopping Center; stop 4, Hepburn and Rehmer (1981)
Location 7: Rhode Island Fm., Providence 7 1/2′ Quad., R.I.: 41°47′46″N, 71°26′57″W: Chestnut Hill Ave., Cranston, R.I.; stop 5, Hepburn and Rehmer (1981)
Location 8: Rhode Island Fm., Providence 7 1/2′ Quad., R.I.: 41°48′10″N, 71°26′48″W: Fenners Ledge, Cranston, R.I.; stop 5, Murray (1981)
Location 9: Rhode Island Fm., East Grenwich 7 1/2′ Quad., R.I.: 41°44′14″N, 71°27′28″W: railroad crossing of Pontiac Ave.; stop 7, Hepburn and Rehmer (1981)

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References

Aronson JL, Hower J (1976) Mechanism of burial metamorphism of argillaceous sediment: 2. Radiogenic argon evidence. Geol Soc Am Bull 73:1167–1170
Ashwal LD, Leo GW, Robinson P, Zartman RE, Hall DJ (1979) The Belchertown Quartz Monzodiorite pluton, west-central Massachusetts, a syntectonic Acadian intrusion. Am J Sci 279:936–969
Bence AE, Albee AL (1968) Empirical correction factors for the electron microanalysis of silicates and oxides. J Geol 76:382–403
Dallmeyer RD (1982) $^{40}Ar/^{39}Ar$ ages from the Narragansett Basin and southern Rhode Island basement terrane: their bearing on the extent and timing of Alleghanian tectonothermal events in New England. Geol Soc Am Bull 93:1118–1130
Dallmeyer RD, Keppie JD (1987) Polyphase late Paleozoic tectonothermal evolution of the southwestern Meguma Terrane, Nova Scotia: evidence from $^{40}Ar/^{39}Ar$ mineral ages. Can J Earth Sci 24:1242–1254
Dallmeyer RD, Lécorché JP (1989) $^{40}Ar/^{39}Ar$ polyorogenic mineral age record within the central Mauritanide orogen, West Africa. Geol Soc Am Bull 101:55–70
Dallmeyer RD, Gil-Ibarguchi I (1990) Age of amphibolitic metamorphism in the ophiolitic unit of the Morais allochthon (Portugal): implications for early Hercynian orogenesis in the Iberian Massif. J Geol Soc London 147:973–878
Dallmeyer RD, Mitchell JG, Pharaoh TC, Reuter A, Andresen A (1988) K-Ar and $^{40}Ar/^{39}Ar$ whole-rock ages of slate/phyllite

from allochthonous basement and cover in the tectonic windows of Finnmark, Norway: evaluating the extent and timing of Caledonian tectonothermal activity. Geol Soc Am Bull 100:1493–1501

Dalrymple GB, Alexander EC, Lamphere MA, Kraker GP (1981) Irradiation of samples for $^{40}Ar/^{39}Ar$ dating using the Geological Survey, TRIGA reactor. US Geol Surv Prof Paper 1176:55

Day HW, Brown VM (1980) Evolution of perthite composition and microstructure during progressive metamorphism of hypersolvus granite, Rhode Island, USA. Contrib Mineral Petrol 72:353–365

Dodson MH (1973) Closure temperature in cooling geochronological and petrological systems. Contrib Mineral Petrol 40:259–274

Dodson MH (1979) Theory of cooling ages. In: Jäger E, Hunziker JC (eds) Lectures in isotope geology. Springer, Berlin Heidelberg New York Tokyo

Dunoyer de Segonzac G (1970) The transformation of clay minerals during diagenesis and low-grade metamorphism: a review. Sedimentology 15:281–346

Enami M (1983) Petrology of pelitic schists in the oligoclase-biotite zone of the Sanbagawa metamorphic terrane, Japan: phase equilibria in the highest grade zone of a high-pressure intermediate type of metamorphic belt. J Meta Geol 1:141–161

Fleming RW (1964) Potassium-argon studies on sedimentary rocks of the Narragansett Basin, Rhode Island-Massachusetts. M.S. thesis, Brown University, Rhode Island, USA

Frank E, Stettler A (1979) K-Ar and $^{39}Ar/^{40}Ar$ systematics of white mica from an alpine metamorphic profile in the Swiss Alps. Schweiz Mineral Petrograph Mitt 59:375–394

Frey M, Teichmüller M, Teichmüller R, Mullis J, Kunzi B, Breitschmid A, Gruner U, Schwizer B (1980) Very low-grade metamorphism in external parts of the Central Alps: Illite crystallinity, coal rank and fluid inclusion data. Eclogae Geolo Helv 73/1:173–203

Gromet LP (1989) Avalonian terranes and late Paleozoic tectonism in southeastern New England: Constraints and problems. In: Dallmeyer RD (ed) Terranes in the circum-Atlantic Paleozoic Orogens. Geol Soc Am Spec Paper 231:193–212

Harrison TM, FitzGerald JD (1986) Exsolution in hornblende and its consequences for $^{40}Ar/^{39}Ar$ age spectra and closure temperatures: Geochim Cosmochim Acta 50:2447–2453

Hepburn JC, Rehmer J (1981) The diagenetic to metamorphic transition in the Narragansett and Norfolk Basins, Massachusetts and Rhode Island. In: Boothroyd JC, Hermes OD (eds) Guidebook to geologic field studies in Rhode Island and adjacent areas: New England Intercollegiate Geologic Conference, 73rd, University of Rhode Island; Kingston, Rhode Island, pp 47–65

Hermes OD, Zartman RE (1985) Late Proterozoic and Devonian plutonic terrane within the Avalon zone of Rhode Island. Geol Soc Am Bull 96:272–282

Hermes OD, Gromet PL, Zartman RE (1981) Zircon geochronology and petrology of plutonic rocks in Rhode Island. In: Boothroyd JC, Hermes OD (eds) Guidebook to geologic field studies in Rhode Island and adjacent areas. 73rd New England Intercollegiate Geologic Conference, University of Rhode Island, Kingston, R.I., pp 315–338

Hurley PM, Fairbairn HW, Pinson WH, Faure G (1960) K-Ar and Rb-Sr minimum ages for the Pennsylvanian section in the Narragansett Basin. Geochim Cosmochim Acta 18:247–258

Hunziker JC, Frey M, Clauer N, Dallmeyer RD, Friedrichsen H, Flehmig W, Hochstrasser K, Roggwiler P, Schwander H (1986) The evolution of illite to muscovite: mineralogical and isotopic data from the Glarus Alps, Switzerland. Contrib Mineral Petrol 92:157–180

Kocis DE, Hermes OD, Cain JA (1978) Petrologic comparison of the pink and white facies of the Narragansett Pier Granite, Rhode Island (abstr). Geol Soc Am Abstr 10:71

Kubler B (1967) La cristallinite de l'illite et les zones tout afait superieure du metamorphisme. Colloque sur les "Etages Tectoniques", 18–21 avril 1966, Festschrift:105–122

Lyons PC, Darrah WC (1978) A late Middle Pennsylvanian flora of the Narragansett Basin, Massachusetts. Geol Soc Am Bull 89:433–438

Lyons JB, Livingston DE (1977) Rb-Sr age of the New Hampshire plutonic series. Geol Soc Am Bull 88:1808–1812

Mori T, Kanehira K (1984) X-ray energy spectrometry for electron probe analysis. J Geol Soc Japan 90:271–285

Mosher S (1983) Kinematic history of the Narragansett Basin, Massachusetts and Rhode Island: constraints on late Paleozoic plate reconstructions. Tectonics 2, pp 327–344

Mosher S, Wood DS (1976) Mechanisms of Alleghanian deformation in the Pennsylvanian of Rhode Island. In: Cameron B (ed) Geology of southeastern New England. 68th New England Intercollegiate Geologic Conference, pp 472–490

Murray DP (1981) Geological setting of coal and carbonaceous material in the Narragansett Basin, southeastern New England. In: Boothroyd JC, Hermes OD (eds) Guidebook to geological field studies in Rhode Island and adjoining areas. 73rd New England Intercollegiate Geologic Conference, University of Rhode Island, Kingston, R.I., pp 175–200

Murray DP, Raben JD (1980) The metamorphism of carbonaceous material, Narragansett Basin, southeastern New England, USA. Industrie Minerale, Les Techniques, June 1980, pp 315–325

Murray DP, Skehan JW (1979) A traverse across the eastern margin of the Appalachian-Caledonide orogen, southeastern New England. In: Skehan JW, Osberg PH (eds) The Caledonides in the USA. I.G.C.P. Project 27, Weston Observatory, Weston, Massachusetts, pp 1–35

Murray DP, Hepburn JC, Rehmer JA (1979) Metamorphism of the Narragansett Basin. In: Evaluation of coal deposits in the Narragansett Basin. Massachusetts. Contract No. J0188022, Final Report, pp 39–47

Murray DP, Raben JD, Lyons PC, Chase HB (1981) The geologic setting of coal and carbonaceous material, Narragansett Basin, south-eastern New England. In: Boothroyd JC, Hermes OD (eds) Guidebook to geologic field studies in Rhode Island and adjacent areas: New England Intercollegiate Geologic Conference, 73rd, University of Rhode Island, Kingston, Rhode Island, pp 175–200

O'Hara KD, Gromet LP (1985) Two distinct Precambrian (Avalonian) terranes in southeastern New England and their late Paleozoic juxtaposition. Am J Sci 285:673–709

Osberg PH, Tull JF, Robinson P, Hon R, Butler JR (1989) The Acadian Orogen: In: The Appalachian-Ouachita orogen in the United States. Hatcher RD, Thomas WA, Viele GW (eds) Decade of North American geology v. F-2, Geol Soc Am, Boulder, Co., pp 179–232

Quinn AW (1971) Bedrock geology of Rhode Island. United States Geological Survey Bull 1295:69

Robbins CS (1972) Radiogenic argon diffusion in muscovite under hydrothermal conditions: (Masters Thesis, unpublish) Brown University, Providence, Rhode Island USA

Robinson P (1979) Bronson Hill anticlinorium and Merrimack synclinorium in central Massachusetts. In: Skehan JW, Osberg PH (eds) The Caledonides in the USA. Geological Excursions in the northeast Appalachians. Weston Observatory, Chestnut Hill, Mass., pp 126–174

Reuter A (1985) Korngrößenabhängigkeit von K-Ar Datierungen und Illit-Kristallinität anchizonaler Metapelite und assoziierter Metatuffe aus dem östlichen Rheinischen Schiefergebirge. Göttinger Arbeiten zur Geologie und Palaontologie 27:91

Reuter A (1987) Implications of K-Ar ages of whole-rock and grain-size fractions of metapelites and intercalated metatuffs within an anchizonal terrane. Contrib Mineral Petrol 97:105–115

Snee LW, Sutter JF, Kelly WC (1988) Thermochronology of economic mineral deposits: dating the states of mineralization at Panasqueira, Portugal by high-precision $^{40}Ar/^{39}Ar$ age spectrum techniques on muscovite. Econ Geol 83:335–354

Sampson SD, Alexander EC (1987) Calibration of the interlaboratory $^{40}Ar/^{39}Ar$ dating standard, MMhb-1. Chem Geol 66:27–34

Skchan SJ, Murray DP, Raben JD (1979) Field Guide to the Narragansett Basin, southeastern Massachusetts and Rhode Island. In: Cameron B (ed) Carboniferous basins of southeastern New England, Guidebook for Field Trip No. 5, Ninth International Congress of Carboniferous Stratigraphy and Geology, Am Geol Institute, Falls Church Va., pp 138–155

Steiger RH, Jäger E (1977) Subcommission on geochronology: convention on the use of decay constants in geo- and cosmochronology. Earth Plan Sci Lett 36:359–362

Teichmüller M, Teichmüller R, Weber K (1979) Inkohlung und Illit-Kristallinitat – Vergleichende Untersuchungen im Mesozoikum und Palaozoikum von Westfalen. Forts Geol Rheinl Westfalen 27:201–276

Takasu A, Dallmeyer RD (1990) $^{40}Ar/^{39}Ar$ mineral age constraints for the tectonothermal evolution of the Sambagawa metamorphic belt, central Shikoku, Japan: a Cretaceous accretionary prism. Tectonophysics 185:111–139

Turner G (1968) The distribution of potassium and argon in chondrites. In: Ahrens LH (ed) Origin and distribution of the elements. Pergamon, New York, pp 378–398

Weber K (1972) Notes on determination of illite crystallinity. Neues Jahrb Mineral Monats 6:267–276

Wiechmann MJ (1979) Mineralogy, petrology and structure of the metamorphosed Pennsylvanian sediments in the Providence area, Rhode Island, Massachusetts: Unpublished M.S. Thesis, Indiana University, Bloomington, USA

Wintsch RP, O'Connell AF, Ranson BL, Wiechmann MJ (1981) Evidence for the influence of fCH_4 on the crystallinity of disseminated carbon in greenschist facies rocks, Rhode Island, USA. Contrib Mineral Petrol 77:207–213

Wintsch RP, Wiechmann MJ, O'Connell AF, Ransom BL (1980) The relationship between carbon crystallinity and metamorphic grade in the Providence area, Rhode Island (abstr). Geol Soc Am Abstr 12:2

Wintsch RP, Sutter JF (1986) A tectonic model for the late Paleozoic of southeastern New England. J Geol 94:459–472

Yamaguchi Y, Akal J, Tomita K (1978) Clinoamphibole lamellae in diopside of garnet lherzolite from Alpe Arami, Bellinzona, Switzerland. Contrib Mineral Petrol 66:263–270

Zartman RE, Hurley PM, Krueger HW, Giletti BJ (1970) A Permian disturbance of K-Ar radiometric ages in New England: its occurence and cause. Geol Soc Am Bull 81:3359–3374

Zartman RE, Naylor RS (1984) Structural implications of some radiometric ages of igneous rocks in southeastern New England. Geol Soc Am Bull 95:522–539

Zartman RE, Hermes OH, Pease MH Jr (1988) Zircon crystallization ages, and subsequent isotopic disturbance events in gneissic rocks of eastern Connecticut and western Rhode Island. Am J Sci 288:376–402

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