[AMERICAN JOURNAL OF SCIENCE, VOL. 287, FEBRUARY, 1987, P. 107-126]

U-Pb ISOTOPIC AND GEOLOGIC EVIDENCE FOR LATE PALEOZOIC ANATEXIS, DEFORMATION, AND ACCRETION OF THE LATE PROTEROZOIC AVALON TERRANE, SOUTHCENTRAL CONNECTICUT

ROBERT P. WINTSCH* and JOHN N. ALEINIKOFF**

ABSTRACT. U-Pb isotopic analyses of zircon and sphene from the Rope Ferry Gneiss of the Waterford Group and of zircon and monazite from a granite dike cutting the gneiss fall along a discordia with intercept ages of 620 ± 3 and 271 ± 4 Ma. The suite of zircons records a simple two-stage history of crystallization in the Late Proterozoic and lead loss in the Permian. The zircons in the granite are pitted and corroded indicating they are xenocrysts; the age and morphology of the zircons and the mineralogy and composition of the host granite indicate that the granite magma was derived by partial melting of Late Proterozoic (Avalonian) rocks. The concordant age of the monazite at ~268 Ma suggests that the granite crystallized in the Permian. This interpretation is supported by the identical concordant age of sphene from the host plagioclase gneiss.

The Late Proterozoic upper intercept age of zircons from the Rope Ferry Gneiss confirms Goldsmith's (1980) assignment of these rocks to the Avalon terrane and precludes the correlation of this gneiss with the Upper Ordovician Turkey Hill belt of Monson Gneiss in the Monson anticline, Bronson Hill terrane. The Permian lower intercept age of the zircon suite indicates high grade metamorphism in the late Paleozoic. The coincidence of the crystallization age of the granite with the lower intercept indicates that this event involved anatexis. Ductile deformation of the granite dike and its host gneiss documents post 268 Ma ductile deformation as well. Thus the Variscan (Alleghenian) orogeny in southern Connecticut involved high grade metamorphism, anatexis, and ductile deformation.

The remarkable linearity of the nine zircon fractions from the two rocks precludes high grade metamorphism between 620 and 270 Ma. It is possible that the Taconic and Acadian orogenies were mild events in these rocks, but more likely that this block of the Avalon terrane was first accreted to North America in the late Paleozoic after the Acadian orogeny. The Permian high grade metamorphism recorded in these rocks thus probably records the culmination of this accretion which led to the final assembly of Pangea.

INTRODUCTION

Bedrock geologic quadrangle mapping in eastern Connecticut and Rhode Island was completed in 1975, just prior to the application of the concept of suspect or exotic terranes to rocks in New England (Williams and Hatcher, 1983). The most important structures identified by this work were major faults and fold nappes (Dixon and Lundgren, 1968; Lundgren and Ebblin, 1972). Subsequent work in southeastern New England over the last 10 yrs has led to the identification of at least four terranes

* Department of Geology, Indiana University, Bloomington, Indiana 47405
** U.S. Geological Survey, Mail Stop 963, Denver Federal Center, Denver, Colorado 80225

(see fig. 1), each with a history distinct in some way from the others (Robinson and Hall, 1980; Hall and Robinson, 1982; Zen, 1983; Zartman and Naylor, 1984). Knowledge of these terranes creates an important new context for the reevaluation of some previous structural interpretations, most of which were formulated before the idea of terrane accretion had been applied to the area.

The region near the west end of the Honey Hill fault in southcentral Connecticut (see fig. 2) is now believed to contain parts of the Avalon, Putnam-Nashoba, Merrimack, and Bronson Hill terranes (Zartman and

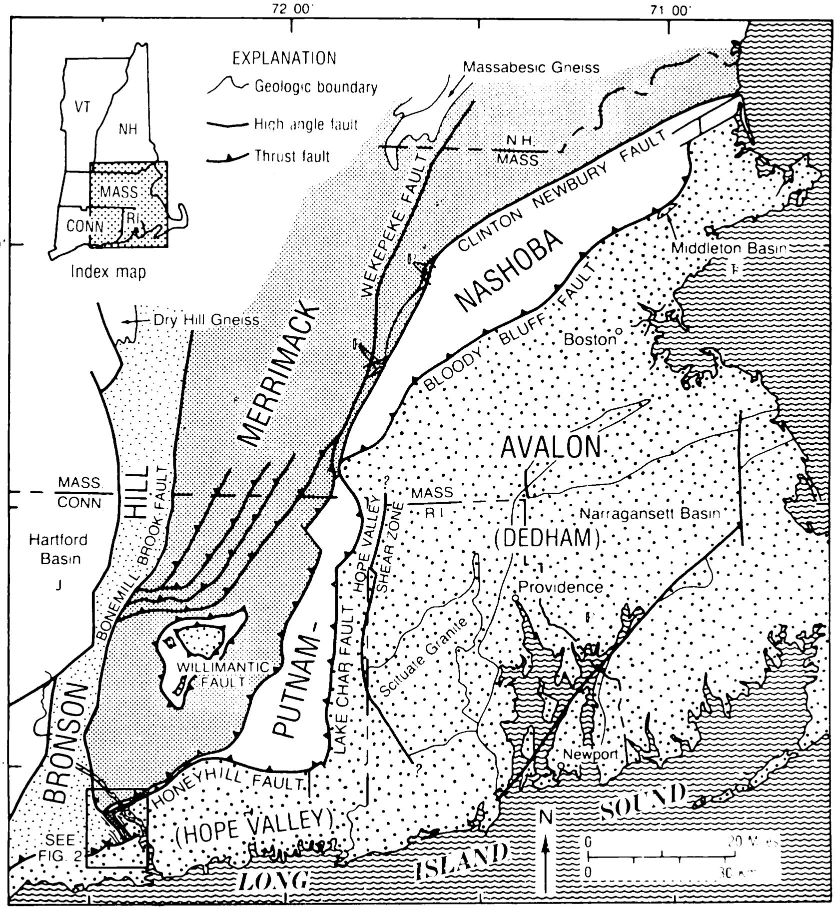


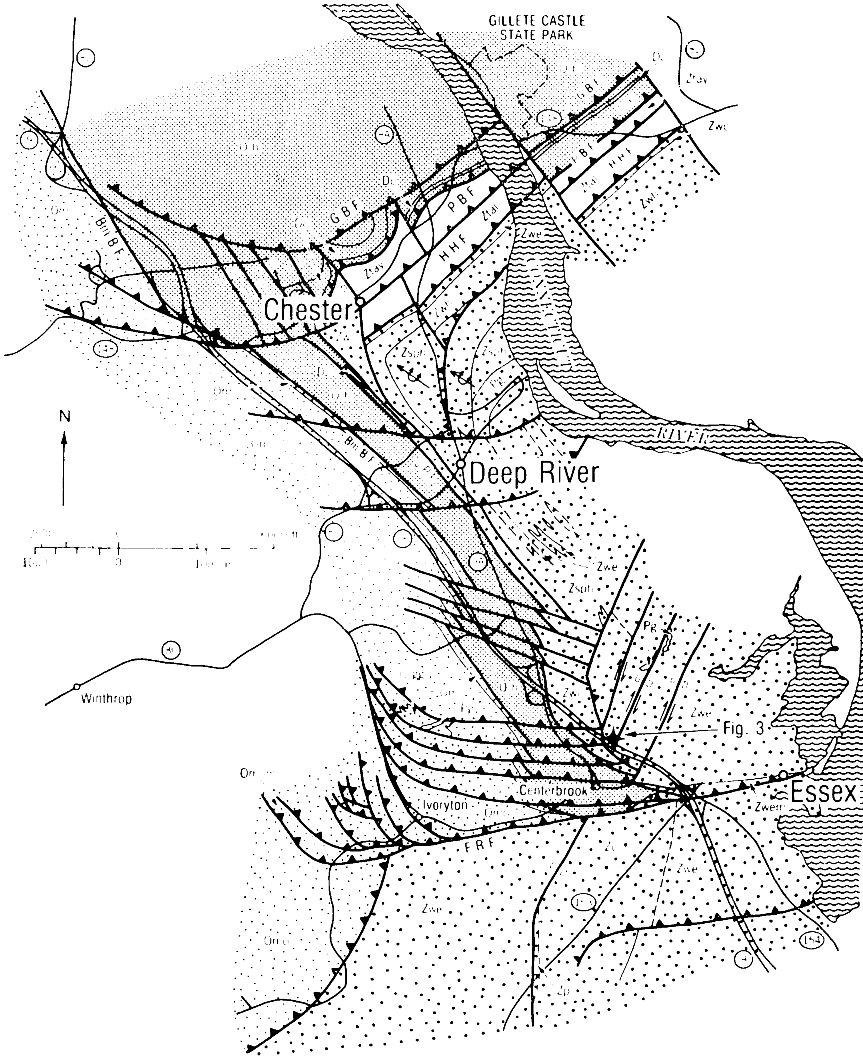
Fig. 1. Generalized tectonic map of southeastern New England, showing the distribution of terranes and major faults (compiled from Zartman and Naylor, 1984; Wintsch, 1985). The map is simplified from that of Rodgers (1985) by not showing rocks now correlated with the Putnam-Nashoba and Merrimack terranes tightly folded around structures south of the Honey Hill fault. The division of the Avalon terrane into the well foliated Hope Valley subterrane and the weakly metamorphosed Dedham subterrane is from O'Hara and Gromet (1985). The Dry Hill Gneiss and Massabesic complex are also late Proterozoic and may be related to the Avalon terrane (Aleinikoff, Zartman, and Lyons, 1979; Zartman and Naylor, 1984). The area of figure 2 is indicated by the box.

Naylor, 1984; Wintsch, 1985). This area is underlain by a great variety of gneisses derived from both igneous and sedimentary rocks. The gneisses have been strongly deformed to produce a complex pattern of domes, basins, antiforms, and synforms (Lundgren, 1962, 1966a). They have also been metamorphosed to upper amphibolite facies conditions and intruded by a suite of relatively late granitic dikes. One important step in the reexamination of the structures in this area in terms of the concept of accreted terranes includes the determination of the ages of the gneisses and the granitic dikes and of the age or ages of metamorphism where possible. In this paper we describe the results of our isotopic analysis of minerals from some rocks of the Avalon terrane and the bearing of these results on local and regional tectonic interpretations.

GEOLOGIC SETTING

The Avalon terrane in southeastern New England is a complex of Late Proterozoic and early to middle Paleozoic sedimentary, igneous, and metamorphic rocks traceable from eastern Massachusetts and Rhode Island in the east to East Haven in the west (Rodgers, 1985). The grade of metamorphism increases from the northeast near Boston where unmetamorphosed sediments occur to the southwest where high grade metamorphism and anatexis in a gneissic complex dominate (Lundgren, 1966b). The continuity of granitic gneisses in a coastal gneissic complex within this terrane was originally recognized by Percival (1842, his unit A). Gneisses of the metasedimentary Plainfield Formation, believed in the past to be Cambrian or older by correlations with fossiliferous quartzites to the northeast, are now included in this complex. These metasedimentary gneisses are associated with or intruded by granitic and granodioritic gneisses. All these gneisses are subsequently cut by thin granitic dikes believed to be related to Permian Westerly and Narragansett Pier granites (Lundgren, 1966b, 1967; Lundgren and Thurrell, 1973) and by Permian pegmatites (Brookins and Armstrong, 1980). Recent isotopic dating of both unmetamorphosed and metamorphosed plutonic igneous rocks in eastern Massachusetts, Rhode Island, and Connecticut (Zartman, Pease, and Hermes, 1983; Zartman and Naylor, 1984; Zartman and Hermes, 1984) confirms a late Proterozoic age for the emplacement of these rocks.

The age of the metamorphism in these rocks has been thought to be Acadian based on correlations to the north in the Bronson Hill terrane (Lundgren, 1962; Robinson and Hall, 1980). However, the age of metamorphism in the eastern part of the Avalon terrane is well constrained to be post-Pennsylvanian by the metamorphism of Pennsylvanian sediments which unconformably overly the Avalonian rocks. Isotopic ages of minerals from western Rhode Island and eastern Connecticut document a Permian disturbance throughout eastern Connecticut (Zartman and others, 1970; Pressel and Armstrong, 1980; Dallmeyer, 1982; Wintsch and Sutter, 1986); Lundgren (1966a) found no direct evidence that the main metamorphism was necessarily Devonian. In spite of the recognition of major Devonian intrusions in Rhode Island (Hermes and Zartman, 1985), the status of pre-Pennsylvanian high grade metamorphism and ductile deformation in Avalonian rocks is uncertain.


GILLETE CASTLE
STATE PARK
Chester
Deep River
Essex
Centerbrook
Ivoryton
Winthrop
N
Fig. 3
GBF
PBF
HHF
FRF
Bm B F
RIVER
Zwe
Zspn
Zwem
Ztav
Zwc
Pg
Om
Dc
154

EXPLANATION

STRATIFIED ROCKS — INTRUSIVE ROCKS — MYLONITIC ROCKS

Pg — Granite

BRONSON HILL TERRANE

Om — Middletown Formation

O?gg — Granite gneiss of Ivoryton

Omo — Monson Formation

Omom — Mylonitic schist and gneiss

MERRIMACK TERRANE

O?h — Hebron Formation

Dc — Canterbury Gneiss

PUTNAM-NASHOBA TERRANE

Tatnic Hill Fm.

- Ztay — Yantic Member
- Ztal — Lower Member

AVALON TERRANE

Zsph — Potter Hill Gneiss of Sterling Plutonic Group

Waterford Group

- Zwc — Amphibolite-rich gneiss of Chester
- Zwh — Plagioclase gneiss of Hadlyme

Zc — Gneiss of Centerbrook

Zwe — Plagioclase orthogneiss of Essex

Zwem — Mylonite schist and gneiss

Zp — Gneiss of Plains Road

Thrust fault — Normal fault — Geologic boundary — Highway

Fig. 2. Geologic map of the Deep River area, emphasizing terrane relationships (from Wintsch, 1985). Note that all terrane boundaries are faults, and that the area has been repeatedly deformed. The location of the outcrop selected for detailed analysis is 0.5 km northeast of Centerbrook.

The tectonic relationship of the Avalon terrane to the adjacent terranes is not well understood, because almost all the western and northern boundary of the Avalon terrane is marked by syn- to post-metamorphic faults (fig. 1). Thus the geology of the highly metamorphosed and structurally complex Deep River area, where the Avalon terrane comes to within 1 km of the Putnam-Nashoba, Merrimack, and Bronson Hill terranes (fig. 2), becomes central to the problem of establishing the relationship of the Avalon terrane to adjacent New England. Based on his quadrangle mapping in the Deep River area completed in the 1950's Lundgren (1962) correlated a plagioclase gneiss west of Deep River with a lithologically similar plagioclase gneiss east of Deep River across a major fold called the Chester syncline. In the new context of accreted terranes, this lithologic correlation now implies the correlation of rocks of the Avalon terrane to the east with rocks of the Bronson Hill terrane to the west. Because of the strong constraints such a correlation places on the tectonic relationship of the Avalon terrane to North America, we undertook the present study to establish the age of the rocks and the metamorphism on the east limb of this critical syncline.

SAMPLING

Samples for this study were collected on a west facing roadcut on Connecticut Route 9, 0.5 km northeast of Centerbrook (see fig. 2). These road cuts did not exist when Lundgren (1964) mapped these rocks as Monson Gneiss on the southern edge of the Selden Neck dome. We chose this locality because of the availability of fresh samples, because of its location near the supposed western limit of the Avalon terrane, and espe-

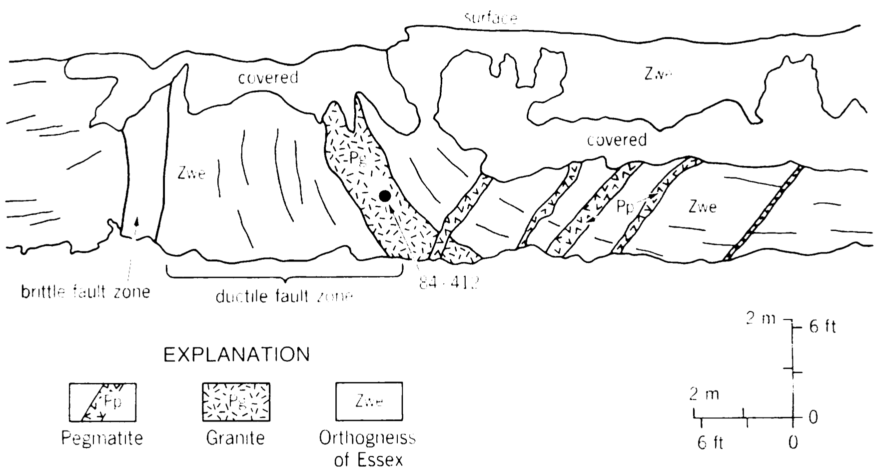


Fig. 3. The geologic relationships among the Late Proterozoic orthogneiss of Essex unit (Zwe) of the Rope Ferry Gneiss, a late, weakly discordant Early Permian anatectic granitic dike (Pg), and strongly discordant Late Permian microcline pegmatites (Pp) (from Wintsch, 1985). The deformation both of the granite dike and the host gneiss demonstrates <270 Ma ductile deformation of these rocks. The location of sample 84-412 is shown. Sample 84-413 was collected 10 m northwest of the granite dike.

cially because the sequence of geologic events at this outcrop could be unambiguously interpreted (fig. 3). The plagioclase gneiss at this locality is now mapped as the intrusive orthogneiss of Essex (Wintsch, 1985) within the Rope Ferry Gneiss of the Waterford Group (Goldsmith, 1980). A thin (1 m) granite dike cuts this gneiss at a low angle to the gneissosity. Both the gneiss and the granite dike are deformed by one of a set of near vertical northeast-trending dextral shear zones. An age of the gneiss at this locality would test its correlation with plagioclase gneisses of either the Late Proterozoic Avalon terrane to the east or with the Upper Ordovician Turkey Hill belt of Monson Gneiss to the west, across the proposed Chester syncline. An age of the granite dike would establish a time later than most of the high grade, ductile deformation, but older than the last stages of deformation in the vertical shear zones.

At this locality, the plagioclase gneiss is a plagioclase–quartz–biotite–hornblende–orthoclase–magnetite–sphene gneiss of tonalitic composition (table 1). Plagioclase and quartz are the coarsest minerals (1-4 mm, avg 2 mm). The unzoned plagioclase (~An 30) and much less common orthoclase grains are equant, and albite, and less often pericline twinning, is present in most grains. In some plagioclase grains curved albite twins are concentrated at grain boundaries. These twins feather out toward the interior of the grain and are probably caused by relatively late ductile deformation of the rock. Large poikiloblastic grains of weakly undulose quartz commonly include plagioclase and less commonly all other minerals. Biotite and hornblende with smooth boundaries occur as subhedral to anhedral grains along grain boundaries between quartz and feldspar. Magnetite occurs as subhedral grains 0.1 to 1.0 mm in diameter. Magnetite is commonly associated with biotite, and larger grains may completely surround biotite. Zircon (usually <50 um) is included in plagioclase or

TABLE 1

Partial chemical analyses* for major (wt percent) and selected trace elements (ppm) and calculated normative mineralogy of Permian granite (84-412) and Rope Ferry Gneiss Member of the Waterford Group (84-413)

Sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3**	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total
84-412	76.6	0.12	12.7	1.03	0.03	0.18	0.93	2.91	5.33	0.12	0.29	100.24
84-413	67.9	0.47	15.5	3.54	0.08	1.07	4.05	4.49	1.10	0.18	0.30	98.68

Sample	Ba	Cr	Cu	Sr	V	Y	Zn
84-412	340	4	4	101	10	19	0
84-413	457	11	4	383	53	33	64

	Normative Mineralogy***								
Sample	Qz	Co	Or	Ab	An	Di	Hy	Il	Ap
84-412	36.63	0.74	31.50	24.62	3.84	0.00	2.01	0.23	0.28
84-413	25.44	0.00	6.50	37.99	18.90	0.02	7.87	0.89	0.42

* Lithium borate fusion and ICP analytical technique of Webster and Wintsch (in review): M. Gilstrap, analyst

** Total iron as Fe_2O_3. *** Total iron as FeO.

biotite. Sphene is restricted to haloes around titaniferous magnetite, where rare haloes of hematite also occur. Such textures provide the only compelling evidence for high temperature metamorphic reaction. These textures as well as the association of magnetite with biotite suggest that the reaction was driven by oxidation and does not indicate any increase in pressure or temperature. Gneissosity is defined by a moderate preferred orientation of biotite, by a strong preferred shape orientation of hornblende grains parallel to it, and is made conspicuous in the field by a concentration of biotite, hornblende, and magnetite in parallel layers.

The crosscutting dike of granitic composition (table 1) contains approximately equal amounts of quartz, microcline, and sodic plagioclase in a mosaic of equant interlocking grains 300 to 500 um in diameter. Most grain boundaries are smooth, but at some triple junctions, small grains of microcline and quartz occur in graphic intergrowth. It also contains ~1 percent each of anhedral biotite and subhedral magnetite and ~2 percent monazite. The strongly concave, indented, and splintery shaped boundaries of biotite inclusions in feldspars suggest biotite dissolution. The lack of reaction products at the biotite-feldspar boundary further suggests that this dissolution occurred prior to crystallization and allows the possibility that the biotite grains are xenocrysts. Zircon occurs as small inclusions in quartz and feldspar. A very weak foliation is defined in this rock by a preferred shape orientation of quartz grains (up to 0.4 $\times$ 3.0 mm long) but not by biotite flakes which are randomly oriented. The only evidence for deformation of the granite found in thin section is a weak undulosity in quartz and microcline.

ANALYTICAL TECHNIQUES

U–Th–Pb isotopic data from zircon, sphene, monazite, and plagioclase from samples of the granite (84-412) and the Rope Ferry Gneiss (84-413) are listed in table 2 and plotted in figure 4. Analytical techniques including mineral separations, chemical extractions, and mass spectrometry are described in Aleinikoff (1985). Common lead corrections in zircon utilized the Stacey and Kramers (1975) model isotopic composition for 620-Ma lead; common lead in sphene and monazite was corrected for using lead in plagioclase from the gneiss. Errors in lead composition ratios range from 0.01 to 0.13 percent for $^{208}Pb/^{206}Pb$ and $^{207}Pb/^{206}Pb$ and from 0.2 to 3 percent for $^{206}Pb/^{204}Pb$ (all fractions except 84-412 (+150)NMD have $^{206}Pb/^{204}Pb$ ratios greater than 5000). Errors in Pb/U ratios range from about 0.45 to 0.85 percent. Regression and error calculations of isotopic data follow the method of Ludwig (1980).

RESULTS

Zircons from the two rock samples have distinctive and different appearances (pl. 1). Zircons from the plagioclase gneiss are euhedral, transparent, light tan, and show no evidence for overgrowths; they have length/width ratios of 2 to 6. Zircons from the granite are euhedral to subhedral, light brown to dark brown with rounded edges and terminations, and corroded and pitted faces and commonly show a core-over-

TABLE 2

U–Th–Pb isotopic data for zircon, monazite, sphene, and plagioclase from rocks in southcentral Connecticut

Sample	Concentration (ppm)			Atomic %				Ages (Ma)			
	U	Th	Pb	^{204}Pb	^{206}Pb	^{207}Pb	^{208}Pb	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{208}Pb/^{232}Th$
				granite dike (84-412)							
(+150)NMD	682	--	60.5	0.0997	81.06	6.224	12.62	506	517	564	--
(-100+150)NMA*	1028	--	89.7	0.0040	84.16	5.048	10.79	528	537	577	--
(-100+150)Mag	2329	--	176.0	0.0134	84.31	5.127	10.55	459	475	549	--
(-150+200)NMD	851	--	68.0	0.0084	85.05	5.111	9.83	489	501	554	--
(-325)NM	1099	--	85.8	0.0049	86.78	5.159	8.05	488	500	553	--
(-325)Mag	1991	--	147.0	0.0339	83.58	5.403	10.98	443	462	558	--
monazite	4349	135,541	1766.0	0.0122	9.27	0.656	90.06	268	267	261	262
				Rope Ferry Gneiss of Waterford Group (84-413)							
(+150)NMD	232	--	18.8	0.0083	83.04	4.982	11.97	485	496	550	--
(+150)NMDA**	239	--	21.4	0.0218	81.08	5.109	13.79	520	530	571	--
(-150+200)NMD	273	--	21.1	0.0007	83.52	4.876	11.61	468	480	539	--
(-325)NMD	321	--	24.3	0.0009	83.18	4.837	11.98	455	467	529	--
(-325)Mag	299	--	23.2	0.0050	82.55	4.874	12.57	462	474	535	--
sphene	310	92.9	14.8	0.1621	79.67	6.476	13.69	268	268	264	270
plagioclase***	0.05	0.02	6.98	1	18.361	15.576	37.971				

* Abraded 115 min, with about 69 percent wt loss.
** Abraded 170 min, with about 63 percent wt loss.
*** Lead composition corrected for *in situ* growth of radiogenic lead for 620 my.
Constants: $^{238}U = 1.55125 \times 10^{-10} yr^{-1}$; $^{235}U = 9.8485 \times 10^{-10} yr^{-1}$; $^{232}Th = 4.9475 \times 10^{-11} yr^{-1}$; $^{238}U/^{235}U = 137.88$ (Steiger and Jäger, 1977)

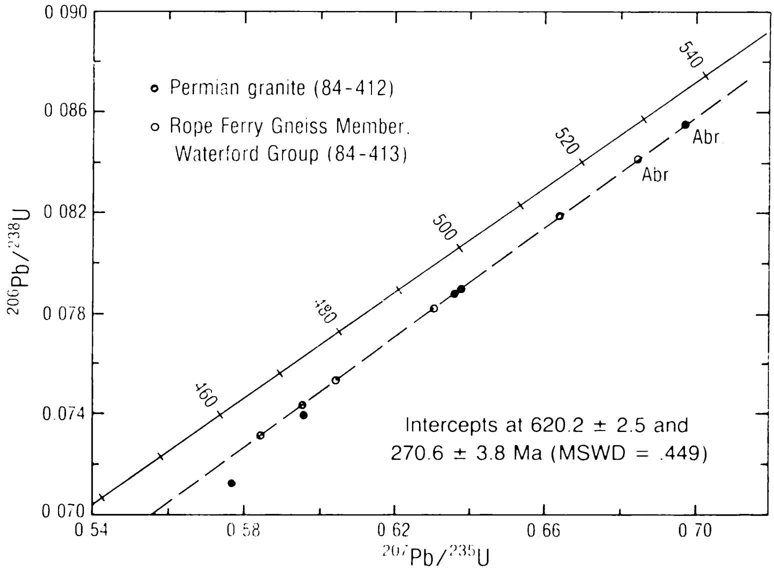


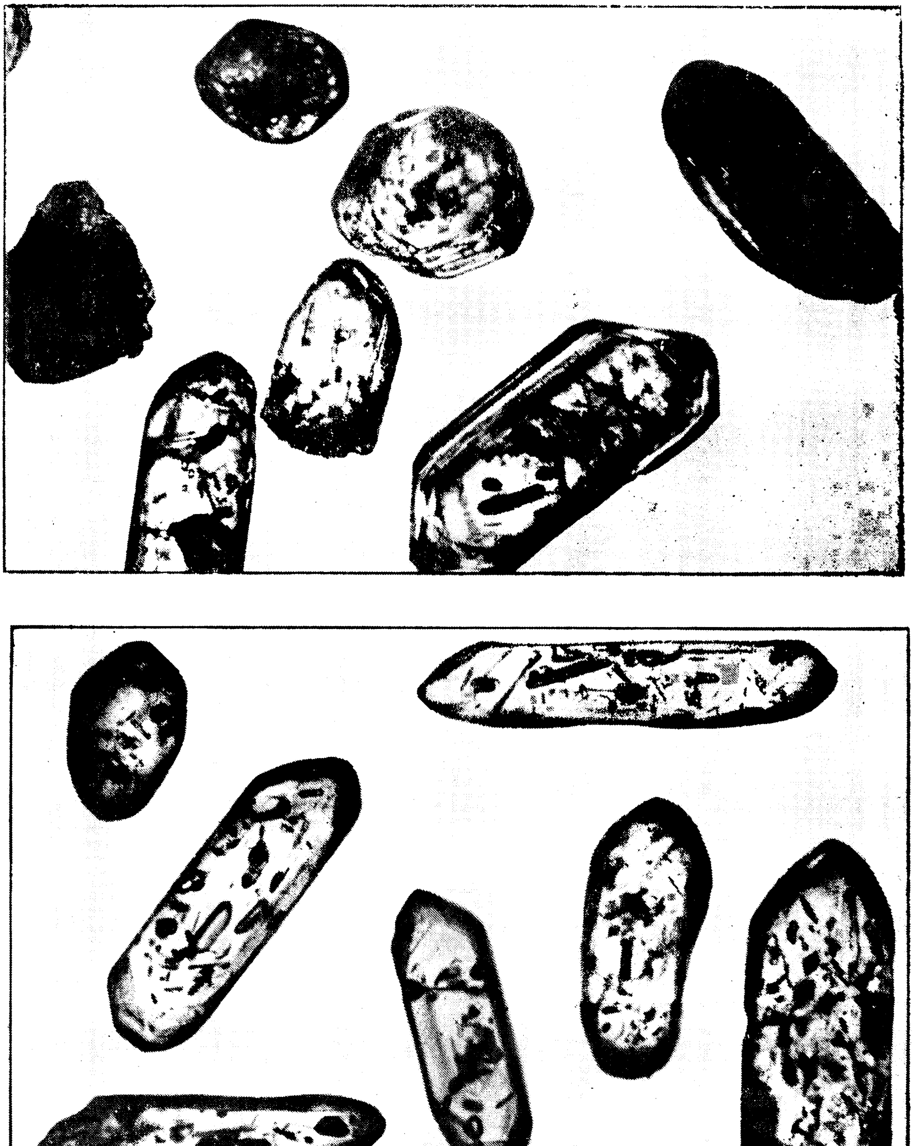
Fig. 4. Concordia diagram for the zircons from granite and the Rope Ferry Gneiss samples. Two abraded fractions are labelled "Abr". Two factions plotting below the discordia were omitted from the regression calculation.

growth relationship; they have length/width ratios of 1 to 4. About 5 to 10 percent of the zircons from the granite are dark brown to opaque; some of these were handpicked from the (—100+150) fraction and analyzed separately (labelled (—100+150)Mag in table 2).

Considerable variation exists in the uranium concentrations both between samples and within the zircon populations from the granite sample. Uranium concentrations in zircons from the gneiss increase from about 230 to 320 ppm U as grain size decreases. Uranium concentrations in zircons from the granite also increase from about 680 to 1990 ppm U with decreasing grain size. Dark zircons that were individually picked from the (—100+150) fraction on the basis of color and morphology had the highest concentration of any fraction: ~ 2330 ppm U. Similarly, dark grains are more abundant in the (—325)Mag fraction than in the (—325)NM fraction, thereby accounting for the near doubling of uranium content in the more magnetic population.

A coarse fraction of zircon from each rock sample was abraded in an attempt to obtain less disturbed (less discordant) isotopic data. Fraction (—100+150)NMA [abraded] from the late granite contained about 34 percent more uranium than the unabraded grains in the same size range, whereas the (+150)NMA [abraded] fraction from the Rope Ferry Gneiss had about the same concentration as the unabraded split (table 2). Thus, cores of zircons from the granite contain considerably more uranium than the rims. This is in contrast to the zircons from the gneiss which are apparently unzoned with respect to uranium. By comparing duration of

PLATE 1



Photomicrographs of the (− 100 + 150) size fraction of zircons from this study. (A) Granite dike, sample 84-412. Note the subhedral to anhedral shape and variable opacity of the zircons. Note also that most grains have cores and overgrowths. The zircons in this sample are interpreted to be xenocrysts (see text). (B) Rope Ferry Gneiss of the Waterford Group, sample 84-413. These zircons are relatively euhedral in shape, with no obvious overgrowths, and are interpreted here as having crystallized in the host Late Proterozoic granodioritic orthogneiss.

abrasion for roughly equal amounts of weight loss, the abrading process also makes apparent the relative difference in uranium concentration between the two samples. Zircons from the granite with significantly greater uranium concentrations were abraded only about two-thirds as long as zircons from the gneiss (table 2). It is therefore likely that these two populations of zircons from the gneiss and the granite are genetically unrelated.

DISCUSSION

Isotopic systematics

Rope Ferry Gneiss.—The five zircon points from the Rope Ferry Gneiss plot along a single chord on a concordia diagram and yield intercepts of 617 ± 6 and 265 ± 9 (MSWD = 0.339). This pattern of the isotopic data indicates a simple two-stage history. Stage 1 involved the crystallization of the zircons and presumably the host granodiorite at ~620 Ma. Stage 2 involved episodic lead loss at ~270 Ma; there is no microscopic evidence for overgrowths as reported by Zartman, Pease, and Hermes (1983). No history prior to 620 Ma is evident from these data, as suggested by the excellent linearity of the points and the fact that the abraded fraction plotted on the same chord as the other fractions. The strong linearity further shows that the zircons did not suffer significant lead loss between 620 and 270 Ma.

Granite dike.—Four of the six zircon fractions analyzed from the granite plot along a chord analytically indistinguishable from the suite of zircons from the Rope Ferry Gneiss. They show no isotopic influence of an Archean core as is present in zircons from the Westerly Granite 30 km to the east (Zartman and Hermes, 1984). The intercept ages of these data array are 621 ± 3 and 272 ± 5 Ma. Plotting somewhat below this line are the two magnetic fractions. As indicated earlier, the zircons in these magnetic fractions have very high uranium concentrations (between 1990 and 2330 ppm), about twice that of the non-magnetic zircons from the granite. Therefore, we suggest that these dark, magnetic, metamict zircons were more susceptible to modern lead loss than the non-magnetic zircons and that they moved off the discordia down toward the origin. Note that their $^{207}Pb/^{206}Pb$ ages are within the age range of the other size fractions, indicative of recent lead loss only.

The four zircons that did not show any evidence of modern lead loss have a history within analytical uncertainty identical to zircons in the gneiss. The granite dike host to these zircons clearly cuts the Rope Ferry Gneiss, and the lack of well developed foliation and the preservation of igneous textures in the granite indicate that granite intrusion post-dates most of the ductile deformation in the host gneiss. Thus the granite must be late Paleozoic in age, and its zircons provide no information about the crystallization history of the granite. The pitted, corroded surfaces and rounded edges and terminations of these zircons indicate that their most recent history involved dissolution rather than growth. Zircons crystallizing at the time of intrusion of the granite would probably have a less corroded appearance, as is common in zircons from most igneous rocks.

A more likely origin for these zircons is that they are xenocrysts, inherited either from the source region or incorporated by assimilation during ascent of the magma. This interpretation is strengthened by the possibility that the biotite flakes are also xenocrysts. The well-constrained upper intercept of the zircon discordia is probably the age of the rocks in the source region. This age is analytically indistinguishable from the age of the intruded gneiss (table 2) as well as from the age of other gneisses correlated with the Avalon terrane (Zartman, Pease, and Hermes, 1983; Zartman and Naylor, 1984). Thus, the source region undoubtedly consisted of rocks of the Avalon terrane.

Direct evidence of the age of crystallization of the granite comes from the isotopic data from monazite (table 2). The monazite data yield a nearly concordant age of 268 Ma, at the lower intercept of the chord established by the zircons. Because the closure temperature of U-Pb systematics in monazite is probably greater than 600°C (Gebauer and Grünenfelder, 1979), this age must closely reflect the age of crystallization of the granite. The possibility that the monazite age is a cooling age is refuted by the analytically identical age of the sphene in the host gneiss (table 2) which has a closure temperature of ~550°C (Hanson, Catanzaro, and Anderson, 1971). Thus, for the monazite and sphene ages to be identical, the granite dike must have crystallized rapidly in the Rope Ferry Gneiss when the gneiss was at the closure temperature of the sphene. This conclusion that the Rope Ferry Gneiss was cooler than the intruding granite magma is supported by the smaller average grain size of the granite (0.6 mm) than the gneiss (2 mm). Thus, the age of intrusion of the granite dike is ~268 Ma, coincident with the lead loss event affecting the included zircon xenocrysts.

If the zircons in the granite are xenocrystic in origin, then a history including partial melting of the enclosing rock might be expected to have caused severe damage to the crystals and also extreme resetting of the U-Pb isotopic systematics. On the contrary, the zircons from the granite are *less* discordant than zircons from the gneiss; that is, the $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages are older. There are at least two possible explanations for this seeming inconsistent behavior. First, dissolution of the rims of the zircons in the anatectic melt would have removed the outer portions of the zircons which are most susceptible to lead-loss. In this natural analogue of an abrading experiment, the points would be driven up the chord on a concordia diagram, and apparent lead loss of the remaining grain would be minimized. Alternatively, if the zircons were zoned, with uranium-poor rims and uranium-rich cores, then radiogenetic lead might be largely inaccessible to diffusion loss. Zircon rims that contain relatively little uranium would be less susceptible to radiation damage and lead-loss, particularly if these rocks had been buried to a depth where self-annealing of fission tracks occurred throughout the Paleozoic until the Permian. In this case, the relatively refractory rim would retard diffusive lead loss from the core, thereby limiting the degree of discordancy.

Evidence for both these possibilities exists. The corroded and pitted morphology of the zircons is evidence that at least some dissolution occurred at the rims. The abraded fraction of the non-magnetic zircons is less discordant than the untreated zircons (table 2), and thus removal of a uranium-rich rim is possible. The second possibility of a zoned zircon may be evaluated by the abrasion experiment. The bulk sample contained 682 ppm U, and the abraded cores contained 1028 ppm U (table 2). During the abrasion, the total sample lost about two-thirds of its weight, indicating that the U content of the average rim was only ~550 ppm. Perhaps the most likely explanation for the unusual discordance pattern is a combination of the above two causes. Uranium-poor rims may have protected the uranium-rich cores from lead loss, and resorption may have removed rims that could have previously lost lead. Thus the apparent lead loss from parent uranium was relatively minimized. In terms of absolute amounts, the granite zircons may have lost more atoms of lead than the gneiss zircons. However, the loss of lead in the gneiss zircons was not accompanied by loss of parent uranium, because, under normal conditions of medium- to high-grade metamorphism, the uranium is structurally bound within the zircon lattice. Thus, daughter product loss by a diffusive mechanism in the gneiss zircons versus [daughter + parent] + daughter loss by dissolution in the granite zircons results in the granite zircons being less discordant than the gneiss zircons.

Geologic Significance

Avalon terrane.—Zircons from both the Rope Ferry Gneiss and the granite dike yield Late Proterozoic upper intercepts, and when regressed together the nine zircons have intercepts of 618 ± 5 and 266 ± 9 Ma. This confirms Goldsmith's (1980) assignment of these rocks to the Avalon terrane, now well documented as having crystallized at ~580-640 Ma (Zartman, Pease, and Hermes, 1983; Zartman and Naylor, 1984; Hermes and Zartman, 1985). Thus, upper intercept ages of zircons document the westward extent of the Avalon terrane from Massachusetts and Rhode Island to at least as far west as the Killingworth dome.

The confirmation of a Late Proterozoic age for the Rope Ferry Gneiss in Essex, Conn. requires revision of some previous structural interpretations in eastern Connecticut. Without the aid of any geochemical information, Lundgren (1962, p. 11) and Dixon and Lundgren (1968) correlated the plagioclase gneisses in the Turkey Hill belt of Monson Gneiss in the Bronson Hill anticlinorium (Lundgren, 1963) with the mineralogically similar plagioclase gneiss analyzed here. The gneisses of the Turkey Hill belt are now known to have a late Ordovician (~440 Ma) crystallization age, similar to the well documented ages of the Oliverian domes in the Bronson Hill terrane (Leo, Zartman, and Brookins, 1984; Zartman and Naylor, 1984; Zartman and Leo, 1985). Thus, the interpretation of the Chester syncline, although reasonable on a lithologic basis, would require the correlation of rocks of Late Proterozoic age with rocks of Late Ordovician age. In light of this new isotopic information, it appears that the Rope Ferry Gneiss analyzed here and the Turkey Hill belt of Monson Gneiss in the Deep River can not be equivalent. This interpretation is in agreement with the chemical composition of our gneiss sample (table 1) which is a tonalitic gneiss similar to other relatively calcic and silica-poor metatonalites and metagranodiorites of the Waterford Group but distinct from the tonalitic to trondhjemitic gneisses of the Bronson Hill anticlinorium (Wintsch and Grant, 1980; Webster and Wintsch, 1984; in review). It is also consistent with the new detailed geologic mapping by Wintsch (1985; see fig. 2) that shows the plagioclase gneisses in the Deep River area are isolated by ductile faults. We conclude that the Bronson Hill and Avalon terranes are not correlative and are not related by folding across the Chester syncline.

If a major syncline does not link plagioclase gneisses east and west of Deep River, then other interpretations in southcentral Connecticut may also require reexamination. In particular, another major syncline, the Hunts Brook syncline (Goldsmith, 1961; Lundgren, 1966a; Dixon and Lundgren, 1968) is thought to contain rocks correlated with the Hebron and Putnam gneisses, now interpreted to belong to the Merrimack and Putnam-Nashoba terranes, respectively. The map shown on figure 1 is simplified from Rodgers (1985) map by not including any major structures within terranes and by not showing rocks currently assigned to the Merrimack terrane in folds and other structures of the Avalon terrane. Although the Hunts Brook and Chester synclines are thought to be related (Dixon and Lundgren, 1968), the doubt that the results reported here cast on the interpretation of the Chester syncline has no direct bearing on the interpretation of the Hunts Brook syncline. More work on these complicated structures is necessary before the constraints these structures place on the tectonic evolution of the Avalon terrane can be assessed.

"Permian Disturbance."—Permian K-Ar mineral ages are characteristic of a large part of eastern New England (Zartman and others, 1970). In the north, these ages probably reflect cooling during uplift and perhaps a Pennsylvanian-Permian thermal event (Lux and Aleinikoff, 1985), but in southern Rhode Island and adjacent Connecticut this disturbance has involved varying amounts of lead-loss from zircons at ~275 Ma and is coincident with metamorphism and ductile deformation in adjacent rocks (Zartman, Pease, and Hermes, 1983; Hermes and Zartman, 1985). The results of this study shed further light on the nature of this disturbance.

As discussed above, the granite dike crystallized at about 268 Ma and therefore documents at least local intrusive igneous activity in the Early Permian. This conclusion is compatible with the earlier work of Lundgren (1966a, b). The evidence that the included zircons are xenocrysts suggests that the granitic magma was derived by partial melting of underlying Avalonian rocks. This possibility is supported by other characteristics as well. The granite contains quartz, microcline, and sodic plagioclase, with minor biotite, magnetite, zircon, and monazite. The lack of strong zoning in the plagioclase, the lack of mafic minerals other than biotite xenocrysts, and the lack of diopside and presence of corundum in the norm (table 1) are all consistent with partial melting of a metasedimentary source. The bulk composition of the granite falls on the cotectic line at about 5kb H_2O (fig. 5), a requirement for minimum melting. Thus, all the available evidence indicates that the granite liquid was derived by

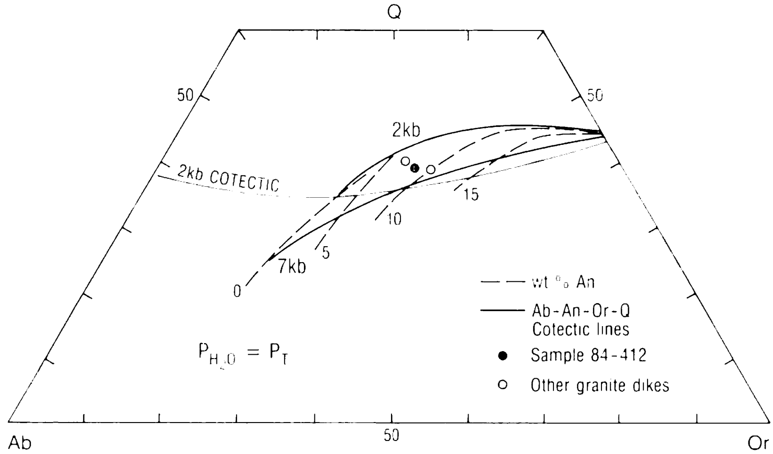


Fig. 5. Projection of the cotectic lines at 2 and 7 kb H_2O in the Ab–An–Or Q system on to the Ab–Or–Q plane. The contours indicate the wt percent in the cotectic liquid. The 2 kb cotectic line in the system Ab–Or–Q is included for reference. Normative compositions of three analyzed samples of Permian granite dikes in Essex show that their compositions are consistent anatectic melting at ~5 kb pressure H_2O. Data for compilation taken from review of Winkler (1979).

partial melting of a metasedimentary source within the Avalon terrane but structurally underlying the Rope Ferry Gneiss sampled. We conclude that the Permian event involved anatexis at temperatures of 650 to 700°C at ~270 Ma.

The granite dike intruded the Rope Ferry Gneiss during the ductile deformation of the gneiss. Early stages of this deformation produced a gneissosity that now dips 40° to 50° northeast. A very weak foliation in the granite suggests that the intrusion of the granite may have been synchronous with the last stages of this deformation. After the granite crystallized (~270 Ma) both it and the host gneiss were deformed by movement on a near vertical right-lateral ductile fault. Thus, the Permian crystallization age of the granite documents important fabric-forming ductile deformation just prior to, as well as shortly after, its intrusion. In the Deep River area, the Permian event involved both anatexis and locally intense ductile deformation. As first suggested by Lundgren (1966a) this textural and structural evidence reflects a broader, higher grade metamorphism than is recognized in Rhode Island but is consistent with an increase in Permian metamorphic intensity to the southwest. Finally, this high grade late Paleozoic metamorphism and anatexis is now sufficiently well-documented in related parts of eastern New England (Narragansett Pier Granite, Kocis, Hermes, and Cain, 1978; Hermes, 1984; Westerly Granite, Zartman and Hermes, 1984; granite of Milford, N.H., Aleinikoff, Zartman, and Lyons, 1979; western Maine, Lux and Guidotti, 1985) that perhaps it should be considered a regional event.

Tectonic Implications

The data collected here help constrain plate tectonic models of the history of the Avalon terrane in southeastern New England. The collision of the Avalon microplate with the already assembled North America + Bronson Hill terrane is believed to have caused the Acadian orogeny in the Devonian (Robinson and Hall, 1980; Rodgers, 1981). Osberg (1978) and Hatch (1982) proposed that an ocean separated Avalonia from the North American plate (Laurentia) at that time, and that this ocean was being closed from the Late Ordovician to the Early Devonian. Citing the lack of geologic evidence for oceanic rocks along the western Avalon boundary, Hall and Robinson (1982) question whether an ocean existed at all. They argue that the late Precambrian granite gneisses in the core of the Pelham dome in central Massachusetts and in the Massabesic Gneiss Complex, New Hampshire (Aleinikoff, Zartman, and Lyons, 1979) are evidence that Avalonian and related basement rocks underlay the Bronson Hill terrane from its creation in the Ordovician. Rodgers (1981) proposed that the Avalonian rocks of the Pelham dome may have been underthrust to that position from the east in Early Devonian and subsequently emerged in the domes formed first in later Devonian time.

Recent paleomagnetic studies suggest a later time of accretion for the Avalon terrane. Paleomagnetic evidence suggests that the Avalon terrane, including the area of figure 1, was ~1500 km south of its present position in the Devonian (Kent, 1982) and was first accreted to Laurentia during the collision of Gondwanaland in the Carboniferous (Kent and Opdike, 1985). Zen (1983), citing these and other geological and geochemical data, endorses a late Paleozoic accretion. A newly identified fault zone in western Rhode Island could resolve some of the above contradictions. O'Hara and Gromet (1985) describe a ductile fault (the Hope Valley shear zone) that divides the Avalon terrane into an eastern weakly metamorphosed (Dedham) subterrane and a more strongly metamorphosed western (Hope Valley) subterrane (see fig. 1). They propose that the eastern subterrane was accreted to Laurentia along the Hope Valley shear zone during the Variscan (Alleghenian) orogeny. This hypothesis does not conflict with paleomagnetic data from the Dedham subterrane but does then require that all Carboniferous displacement (up to 1500 km) occur in the Hope Valley shear zone and leaves the Hope Valley subterrane unconstrained relative to motions of the eastern Avalonian subterrane.

Our results from rocks in O'Hara and Gromet's (1985) Hope Valley subterrane make the interpretation of an early accretion of this subterrane more difficult, because the zircons provide no evidence of metamorphism between 620 and 270 Ma. If the Hope Valley subterrane had been buried to a temperature of greater than 200° to 250°C, then self-annealing of fission tracks within the zircons may have prevented lead loss from occurring during a low grade metamorphic event between 620 and 270 Ma. However, the exceptional linearity of the zircon data precludes disturbance of the isotopic systematics by high grade metamorphism prior to the Permian. Note that even zircons with greater than 1990 ppm U (the (−100+150)Mag and (−325)Mag fractions from the granite) have nearly identical $^{207}Pb/^{206}Pb$ ages as non-magnetic zircons from the same or similar size fractions, indicating that only modern lead loss has changed the Pb/U ratios of the uranium-rich zircons. Two explanations for these results are possible: (1) either both the Taconic and Acadian orogenies were very mild in southcentral Connecticut, or (2) the Hope Valley subterrane was not accreted until post-Acadian times. Because high grade Acadian metamorphism is well documented in central New England (Thompson and Norton, 1968), the possibility of only low grade metamorphism in southern New England seems doubtful. A more likely explanation is that the Late Proterozoic gneisses of the Avalon terrane of southeastern New England were not accreted to North America until the Permian and, thus, were not involved in the early to mid Paleozoic tectonism/deformation/metamorphism of the Bronson Hill Anticlinorium and Kearsarge-Central Maine Synclinorium of central and northern New England (Lyons, Bondetti, and Aleinikoff, 1982). Following this logic, structures like the Hunts Brook syncline must also be Permian in age, as originally proposed by Lundgren (1967).

CONCLUSIONS

We believe that the results of this study provide compelling evidence that the "Permian disturbance" in southern New England involved both high grade ductile deformation and anatexis of the Avalon terrane. The Late Proterozoic age of the rocks on the east limb of the proposed Chester syncline confirms their correlation to the Avalon terrane and precludes their correlation with Late Ordovician rocks in Bronson Hill terrane. The remarkable linearity of the nine zircon fractions indicates that the rocks probably did not suffer high grade metamorphism between 620 and ~270 Ma. This further suggests that the Avalon terrane escaped the Acadian and Taconic orogenies, because it first accreted to North America in late Carboniferous time.

ACKNOWLEDGMENTS

We thank R. Zartman for encouragement to undertake this study, and H. R. Dixon, R. Goldsmith, L. Lundgren, S. Quarrier, M. Pease, and R. Zartman for many helpful discussions. R. Goldsmith, L. Lundgren, J. Sutter, and R. Zartman made helpful comments on an earlier draft of this manuscript. We thank G. Dipple and R. Ogg for help in sample preparation, L. B. Fischer and L. Finiol for chemical extractions, and A. Held, R. Hill, and W. Moran for help in manuscript preparation. This work was partially supported by NSF grant EAR 83-13807.

REFERENCES

Aleinikoff, J. N., 1985, Isotopic and morphologic evidence for the age of the Fordham Gneiss: Am. Jour. Sci., v. 285, p. 459-479.

Aleinikoff, J. N., Zartman, R. E., and Lyons, J. B., 1979, U-Th-Pb geochronology of the Massabesic Gneiss and the granite near Milford, south-central New Hampshire: New evidence for Avalonian basement and Taconic and Alleghenian disturbances in eastern New England: Contr. Mineralogy Petrology, v. 71, p. 1-11.

Brookins, D. G., and Armstrong, R. L., 1980, New K-Ar dates for pegmatites and host rocks, Portland, Connecticut: Contr. Geochronology in Connecticut, II: Connecticut Geol. Nat. History Survey, Rept. Inv., no. 10, p. 37-40.

Dallmeyer, R. D., 1982, $^{40}Ar/^{39}Ar$ ages from the Narragansett basin and southern Rhode Island basement terrane: Their bearing on the extent and timing of Alleghenian tectonothermal events in New England: Geol. Soc. America Bull., v. 93, p. 1118-1130.

Dixon, H. R., and Lundgren, L. W., 1968, Structure of eastern Connecticut, *in* Zen, E-an, White, W. S., Hadley, J. B., and Thompson, J. B., Jr., eds.; Studies of Appalachian Geology, northern and maritime: New York, Wiley Intersci. Publishers, p. 219-229.

Gebauer, D., and Grünenfelder, 1979, U-Th-Pb dating of minerals: *in* Jäger, E., and Hunziker, J. C., eds., Lectures in Isotope Geology: New York, Springer-Verlag, p. 105-131.

Goldsmith, Richard, 1961, Axial plane folding in southeastern Connecticut: U.S. Geol. Survey Prof. Paper 424-C, p. C54-C57.

———— 1980, Stratigraphic names in the New London area, Southeastern Connecticut: A revision, *in* Sohl, N. F., and Wright, W. B., Changes in Stratigraphic nomenclature by the U.S. Geological Survey, 1979: U.S. Geol. Survey Bull. 1502-A, p. 91-103.

Hall, L. M., and Robinson, Peter, 1982, Stratigraphic-tectonic subdivisions of Southern New England, *in* St. Julien, P. and Belind, J., eds., Major structural zones and faults of the Northern Appalachians: Geol. Assoc. Canada, Spec. Paper 24, p. 15-43.

Hanson, G. N., Catanzaro, E. J., and Anderson, D. H., 1971, U-Pb ages for sphene in a contact metamorphic zone: Earth Planetary Sci. Letters, v. 12, p. 231-237.

Hatch, N. L., Jr., 1982, Taconian Line in western New England and its implications to Paleozoic tectonic history, *in* St. Julien, P., and Belind, J., eds., Major structural zones and faults of the northern Appalachians: Geol. Assoc. Canada Spec. Paper 24, p. 67-85.

Hermes, O. D., 1984, Characteristics of igneous activity in the Avalon terrane of Rhode Island: Geol. Soc. America Abs. with Programs, v. 16, p. 23.

Hermes, O. D., and Zartman, R. E., 1985, Late Paleozoic and Devonian plutonic terrane within the Avalon Zone of Rhode Island: Geol. Soc. America Bull., v. 96, p. 272-282.

Kent, D. V., 1982, Paleomagnetic evidence for post-Devonian displacement of the Avalon platform (Newfoundland): Jour. Geophys. Research, v. 87, p. 8709-8716.

Kent, D. V., and Opdyke, N. D., Multicomponent magnetizations from the Mississippian Mauch Chunk Formation of the central Appalachians and their tectonic implications: Jour. Geophys. Research, v. 90, p. 5371-5383.

Kocis, D. E., Hermes, O. D., and Cain, J. A., 1978, Petrologic comparison of the pink and white facies of the Narragansett Pier Granite, Rhode Island: Geol. Soc. America Abs. with Programs, v. 10, p. 71.

Leo, G. W., Zartman, R. E., and Brookins, D. G., 1984, Glastonbury gneiss and mantling rocks (a modified Oliverian dome) in south-central Massachusetts and north-central Connecticut: Geochemistry, petrogenesis, and radiometric ages: U.S. Geol. Survey Prof. Paper 1295, 45 p.

Ludwig, K. R., 1980, Calculation of uncertainties of U-Pb isotopic data: Earth Planetary Sci. Letters, v. 46, p. 212-220.

Lundgren, Lawrence, Jr., 1962, Deep River area, Connecticut: Stratigraphy and structure: Am. Jour. Sci., v. 260, p. 1-23.

———— 1963, The bedrock geology of the Deep River quadrangle: Connecticut Geol. Nat. History Survey, Quad. Rept. 13, 42 p.

———— 1964, The bedrock geology of the Essex quadrangle, with map: Connecticut Geol. Nat. History Survey Quad. Rept. 15, 38 p.

———— 1966a, Bedrock geology of the Hamburg quadrangle: Connecticut Geol. Nat. History Survey Quad. Rept. 19, 41 p.

———— 1966b, Muscovite reactions and partial melting, southeastern Connecticut: Jour. Petrology, v. 7, p. 421-453.

———— 1967, The bedrock geology of the Old Lyme quadrangle, with map: Connecticut Geol. Nat. History Survey, Quad. Rept. 21, 30 p.

Lundgren, Lawrence, and C. Ebblin, 1972, Honey Hill fault in eastern Connecticut: regional relations: Geol. Soc. America Bull., v. 83, p. 2773-2794.

Lundgren, Lawrence, and Thurrell, R. F., 1973, Bedrock geology of the Clinton quadrangle with map: Connecticut Geol. Nat. History Survey, Quad. Rept. 29, 22 p.

Lux, D. R., and Aleinikoff, J. N., 1985, ^{40}Ar-^{39}Ar and U-Pb geochronology of the Songo pluton, western Maine: Geol. Soc. America Abs. with Programs, v. 17, p. 32.

Lux, D. R., and Guidotti, C. V., 1985, Evidence for extensive Hercynian metamorphism in western Maine: Geology, v. 13, p. 696-700.

Lyons, J. B., Bondette, E. L., and Aleinikoff, J. N., 1982, The Avalon and Gander zones in central eastern New England, *in* St. Julien, P., and Beland, J., eds., Major structural zones and faults of the northern Appalachians: Geol. Assoc. Canada, Spec. Paper 24, p. 43-66.

O'Hara, K. D., and Gromet, L. P., 1985, Two distinct Late Precambrian (Avalonian) terranes in southeastern New England and their Late Paleozoic juxtaposition: Am. Jour. Sci., v. 285, p. 673-709.

Osberg, P. H., 1978, Synthesis of the geology of the northeastern Appalachians, U.S.A.: IGCP Project 27, U.S.A., Contr. 1. Caledonian-Appalachian Orogeny of the North Atlantic Region: Canada Geol. Survey, Paper 78-13, p. 137-147.

Percival, J. G., 1842, Report on the geology of the state of Connecticut: New Haven, Osborn and Baldwin, 495 p., map.

Pressel, D. C., and Armstrong, R. L., 1980, K-Ar dates for granitic rocks and the Honey Hill fault, southeastern Connecticut: Contributions to Geochronology in Connecticut, II: Connecticut Geol. Nat. History Survey Rept. Inv. 10, p. 1-4.

Robinson, P., and Hall, L. M., 1980, Tectonic significance of southern New England, *in* Wones, D. R., ed., Proceedings "The Caledonides in the U.S.A.": Virginia Polytechnic Inst. and State Univ. Mem., v. 2, p. 73-82.

Rodgers, John, 1981, The Merrimack synclinorium in northeastern Connecticut: Am. Jour. Sci., v. 281, p. 176-186.

——— 1985, Compiler, Bedrock geologic map of Connecticut: Connecticut Geol. Nat. History Survey, scale 1:125,000.

Stacey, J. S., and Kramers, J. D., 1975, Approximation of terrestrial lead isotope evolution by a two-stage model: Earth Planetary Sci. Letters, v. 26, p. 207-221.

Steiger, R. H., and Jäger, E., 1977, Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronogy: Earth Planetary Sci. Letters, v. 36, p. 359-362.

Thompson, J. B., Jr., and Norton, S. A., 1968, Paleozoic regional metamorphism in New England and adjacent areas, *in* Zen, E-an, White, W. S., Hadley, J. B., and Thompson, J. B., Jr., eds., Studies of Appalachian Geology: Northern and Maritime: New York, John Wiley Intersci., p. 319-327.

Webster, J. R., and Wintsch, R. P., 1984, Major element geochemistry and possible subdivision of the Killingworth Dome, Southcentral Connecticut [abs.]: Geol. Soc. America Abs. with Programs, v. 16, p. 70.

——— in review, Petrochemistry and origin of the Killingworth dome rocks, Bronson Hill anticlinorium, southcentral Connecticut: Geol. Soc. America Bull., v.

Williams, H., and Hatcher, R. D., Jr., 1983, Appalachian suspect terranes, *in* Hatcher, R. D., Jr., Williams, Harold, and Zietz, Isidore, eds., Contributions to the Tectonics and Geophysics of Mountain Chains: Geol. Soc. America, v. 158, p. 33-53.

Winkler, H. G. F., 1979, Petrogenesis of Metamorphic rocks, 5th ed.: New York, Springer-Verlag, 348 p.

Wintsch, R. P., 1985, Bedrock geology of the Deep River area, Connecticut, *in* Tracy, R., ed., Guidebook for fieldtrips in Connecticut and south central Massachusetts: Connecticut Geol. Nat. History Survey, Guidebook 6, in review.

Wintsch, R. P., and Grant, N. K., 1980, Major element, rare earth element and Sr isotope geochemistry of "Monson Gneisses," eastern Connecticut [abs.]: Geol. Soc. America Abs. with Programs, v. 12, no. 2, p. 89.

Wintsch, R. P., and Sutter, J. F., 1986, A tectonic model for the late Paleozoic of southeastern New England: Jour. Geology, v. 94, (in press).

Zartman, R. E., and Hermes, O. D., 1984, Evidence from inherited zircon for Archean basement under the southeastern New England Avalon terrane [abs.]: Geol. Soc. America Abs. with Programs, v. 16, p. 704.

Zartman, R. E., Hurley, P. M., Krueger, H. W., and Giletti, B. J., 1970, A Permian disturbance of K-Ar radiometric ages in New England — its occurrence and cause: Geol. Soc. America Bull., v. 81, p. 3359-3373.

Zartman, R. E., and Leo, G. W., 1985, New radiometric ages on gneisses of the Oliverian domes in New Hampshire and Massachusetts: Am. Jour. Sci., v. 285, p. 267-280.

Zartman, R. E., and Naylor, R. S., 1984, Structural implications of some radiometric ages of igneous rocks in southeastern New England: Geol. Soc. America Bull., v. 95, p. 522-539.

Zartman, R. E., Pease, M. M., Jr., and Hermes, O. D., 1983, Encroachment of the Late Paleozoic variscan front on southern New England [abs.]: Geol. Soc. America Abs. with Programs, v. 15, p. 147-148.

Zen, E-an, 1983, Exotic terranes in the New England Appalachians — limits, candidates, and ages: A speculative essay, *in* Hatcher, R. D., Jr., Williams, H., and Zietz, I., eds., Contributions to the tectonics and geophysics of mountain chains: Geol. Soc. America Mem. 158, p. 55-81.