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URANIUM–THORIUM–LEAD AGES OF THE HIGHLANDCROFT PLUTONIC SUITE, NORTHERN NEW ENGLAND

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ABSTRACT. Six of the eight identified plutons of the Highlandcroft Plutonic Suite of northern New England have been dated by the U–Th–Pb method. Along the main northeast trend of these plutons, ages range from about 443 to 453 Ma (from north to south, Attean Quartz Monzonite: 443 ± 4 Ma; Adamstown Granite: about 453 Ma; and Highlandcroft Granodiorite: 450 ± 5 Ma) and establish the fact, first suggested by Naylor (1969), that the Highlandcroft and Oliverian Plutonic Suites are coeval. The East Inlet pluton (granodiorite), located 20 km northwest of the Highlandcroft belt, is interpreted to have a slightly younger age of 430 ± 4 Ma. Zircons from two other plutons, the Fairlee Quartz Monzonite and the Lost Nation pluton (quartz diorite), yield scattered isotopic data, and their ages have not been established, but geologically the Fairlee Quartz Monzonite may be coeval with the East Inlet pluton.

The Lost Nation, Fairlee, East Inlet, and Highlandcroft plutons show varying degrees of contamination by xenocrystic zircon and demonstrate that at least part of the Highlandcroft Plutonic Suite ascended through, or was derived from, Proterozoic material of probably about 1.5 Ga age. We propose, on the basis of age data, geologic constraints, and time-scale consideration, that Highlandcroft Suite magmatism was continuous from the Middle or Late Ordovician throughout at least the Early to Middle Silurian.

INTRODUCTION

The Highlandcroft Plutonic Suite has as its type intrusion (Billings, 1937) a small granodiorite stock on the western outskirts of Littleton, N.H. (4 in fig. 1). Eight stocks in northern New Hampshire and west-central Maine (fig. 1) are now assigned to the suite. With the exception of the Attean Quartz Monzonite (1 in fig. 1), which intrudes Proterozoic granulite facies diamictites of the Chain Lakes massif (Naylor and others, 1973), all other stocks of the Highlandcroft Suite intrude low-grade Ordovician-Cambrian(?) and, in one case, Early to Middle Silurian metasediments and metavolcanics.

The type-Highlandcroft Granodiorite of Billings (1937) lies unconformably below and, thus, predates the Upper Silurian (Ludlow-Pridoli) Fitch Formation, recently dated paleontologically by Harris, Hatch, and Dutro (1983) using conodonts. It has also been shown to be older than conglomerate of the Upper Llandovery (late Early Silurian) Clough

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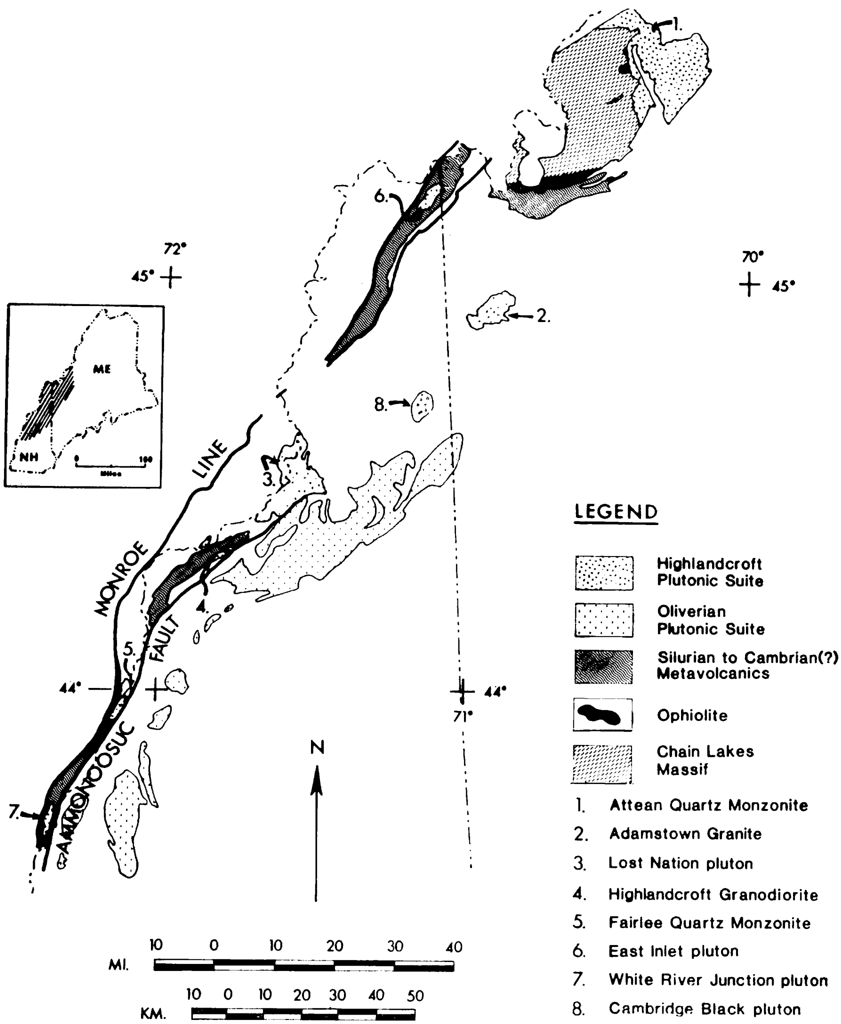


Fig. 1. Distribution of Highlandcroft plutons in northern New Hampshire and central western Maine. Map modified from Billings (1956) and Moench (1984).

Quartzite (Billings, 1937, p. 499). The Attean Quartz Monzonite is buried unconformably beneath an Upper Silurian conglomerate (Albee and Boudette, 1972). Therefore, part of the Highlandcroft Plutonic Suite is geologically constrained to be older than late Early Silurian and younger than Ordovician-Cambrian(?) (or Early Silurian(?)). The Fairlee Quartz Monzonite, by contrast, intrudes the Lower to Middle Silurian Perry Mountain Formation (R. H. Moench, verbal commun., 1985). All plutons of the Highlandcroft Suite have been regionally metamorphosed during the Devonian Acadian orogeny, but Rumble and Finnerty (1974) showed an earlier Taconian(?) contact metamorphism peripheral to the Highlandcroft intrusives.

Lead-alpha ages reported by Lyons and others (1957) for the Highlandcroft Suite are invalid, as subsequently demonstrated by Rose and Stern (1960), who, using an improved method for determining lead, obtained five lead-alpha ages ranging from 395 to 500 Ma for the Attean Quartz Monzonite (Albee and Boudette, 1972, p. 88) — a rather inconclusive result. Boone, Boudette, and Moench (1970, p. 19) have quoted an "informal" U–Th–Pb zircon age of 470 Ma for the Attean Quartz Monzonite on the basis of unpublished data of L. T. Silver. That age has been widely quoted in the literature on New England geology. Potassium-argon and rubidium-strontium muscovite ages of 433 and 457 Ma (using the old decay constants), based upon unpublished data of R. E. Zartman and F. C. Canney for a greisen in the Attean intrusion were also quoted by Boone, Boudette, and Moench (1970). Using data from two whole-rock samples and an assumed $^{87}Sr/^{86}Sr$ initial ratio of 0.706, Naylor (1969) calculated a possible Rb–Sr age of 450 ± 40 Ma for the Fairlee Quartz Monzonite (5 in fig. 1). Because most Rb–Sr and U–Th–Pb ages for the Oliverian Plutonic Suite (fig. 1) also fall in the 440 to 450-my range, Naylor proposed that the Highlandcroft and Oliverian Suites are coeval, but that they crystallized at different crustal levels. Data from four zircon fractions, including a "total" population, from the East Inlet pluton (6 in fig. 1) yield an upper concordia intercept of about 425 my (Eisenberg, ms). This body lies about 20 km west of the main Highlandcroft trend. Thus, previously reported isotopic ages for the Highlandcroft Suite span the time interval from 425 to 470 my.

Petrochemical and petrologic data on the Highlandcroft Plutonic Suite have been determined by Pogorzelski (ms). As also reported by Billings (1956), there is a considerable range in composition, including diorite, tonalite, granodiorite, and granite. This range is less than that for the Oliverian Suite (gabbro, tonalite, granodiorite, granite, and syenite), and the latter series is, in general, more felsic, more highly metamorphosed, and more gneissic than the Highlandcroft Suite. New U–Pb zircon data for core gneisses of six Oliverian domes (Zartman and Leo, 1985) plot as an approximately colinear array on a concordia diagram that has an upper intercept age of 444 Ma.

In this paper, we present new U–Th–Pb isotopic analyses of zircons from six of the eight plutons now assigned to the Highlandcroft Plutonic Suite. The southernmost and smallest of the plutons, a small lit–par–lit complex in White River Junction, Vt. (7 in fig. 1), and a body in north-central New Hampshire, informally named the Cambridge Black pluton (8 in fig. 1, R. H. Moench, written commun., 1985) have not been dated. G. W. Leo suggests (oral commun., 1985) that the lit–par–lit trondhjemite-greenstone complex at White River Junction, Vt., is related to the Ammonoosuc Volcanics.

DESCRIPTION OF SAMPLES

A brief petrographic description of these rocks, all of which have been regionally metamorphosed to the greenschist facies, follows. Latitudes and longitudes for dated samples are listed in the appendix.

The Attean Quartz Monzonite (1 in fig. 1) from the type locality (Albee and Boudette, 1972) is a mottled green to pink, medium- to coarse-grained granite. It has a weak flow foliation but has not been penetratively deformed. Microcline, hornblende, quartz, and sphene are pristine, but biotite has been chloritized, and plagioclase extensively sericitized and epidotized. The Adamstown Granite of Green and Guidotti (1968) (2 in fig. 1) is a strongly deformed granodiorite, containing quartz, sericitized plagioclase, microcline, chlorite, sericite, epidote, and opaques. Scheelite and molybdenite are two unusual accessories. The Lost Nation pluton (quartz diorite) (3 in fig. 1) is an unsheared, light-green, medium-grained rock consisting of hornblende, chloritized biotite, epidote, opaques, sericitized plagioclase, microcline, and quartz. Highlandcroft Granodiorite of Billings (1937) (4 in fig. 1) is a heavily sheared green granite, with microcline, quartz, sericitized plagioclase, chloritized biotite, epidote, and opaques as major minerals; approx 5 percent of hydrothermal calcite has been introduced, presumably at the time the rock was sheared. Fairlee Quartz Monzonite (5 in fig. 1) is a coarse-grained, subporphyritic, greenish-gray to pink rock, sheared near its margins and generally showing cataclastic structure. Microcline perthite, quartz, sericitized plagioclase, chloritized biotite, epidote, sphene, and opaques constitute its mineralogy. The East Inlet pluton (6 in fig. 1) is a light-green, jointed, but non-foliated granodiorite with a micro-granophyric texture. Microcline, quartz, albite, epidote, chlorite, sericite, and opaques are the major minerals.

ANALYTICAL TECHNIQUES

Samples weighing about 40 kg were collected from fresh road cuts or quarries and in all cases were trimmed to remove weathered or fractured surfaces. Crushing, grinding, and initial concentration of zircon were carried out at Dartmouth College. Final purification of zircon concentrates and analytical work were carried out in the isotope geology laboratory of the U.S. Geological Survey in Denver.

Zircons from each sample were split into several size and magnetic fractions generally weighing between 1 and 15 mg. One size fraction from sample Me/O (Adamstown Granite) was abraded, and only rounded, residual cores were analyzed. Decomposition and ion-exchange chemistry were modified from Krogh (1973). Isotopic ratios were measured on an NBS 30-cm mass spectrometer with digital control and data processing.

Uranium, thorium, and lead concentrations are considered accurate to ± 1 percent. Lead composition ratios are ± 0.1 percent except $^{206}Pb/^{204}Pb$ ratios of greater than 1000, which are probably accurate to 3 to 5 percent. Common lead corrections have been made by subtracting lead equal in analyzed amount (<2 mg) and isotopic composition ($^{204}Pb:^{206}Pb:^{207}Pb:^{208}Pb$ = 1:18.7:15.6:38.2) to a laboratory blank. The remaining ^{204}Pb was assumed to be that of 450-Ma old "model" lead where ^{204}Pb:^{206}Pb:^{207}Pb:^{208}Pb = 1:17.95:15.586:37.745 (Stacey and Kramers, 1975). Age calculations used decay constants and the present-day uranium isotopic composition of Steiger and Jäger (1977). Best-fit line and uncertainty calculations used the methods of York (1969) and Ludwig (1980).

Zircon morphology.—The morphology of zircons is an important factor for interpretation of isotopic data. Plate 1-A to -F consists of representative photomicrographs of zircons from each dated sample of the Highlandcroft Plutonic Suite. In general, all populations contain zircons that are euhedral, are zoned, and have typical (for granitic rocks) length-to-width (L/W) ratios in the range of 1 to 6:1. Color, shape, and density of inclusions vary significantly.

A. Attean Quartz Monzonite: zircons are euhedral, have L/W of 2-6:1, are fairly clear, well-faceted, and contain relatively few opaque inclusions.

B. Adamstown Granite: zircons are euhedral, have L/W of only 1-2:1, and contain many opaque inclusions. They are moderate to dark brown, some with rounded cores and zoned, euhedral, lighter overgrowths.

C. Lost Nation pluton: zircons are subhedral to euhedral, have L/W of 2-4:1, are light brown to clear, and contain very few inclusions or discernable xenocrystic core material.

D. Highlandcroft Granodiorite: zircons are euhedral, have L/W of 1-4:1, are light to moderate brown, and contain few inclusions.

E. Fairlee Quartz Monzonite: zircons are subhedral to euhedral, have L/W of 1-5:1, and are light to dark brown. Some grains are inclusion free and nearly clear; others contain very dark rounded cores and opaque inclusions.

F. East Inlet pluton: zircons are euhedral, have L/W of 2-6:1, and are light to moderate brown; most grains contain inclusions.

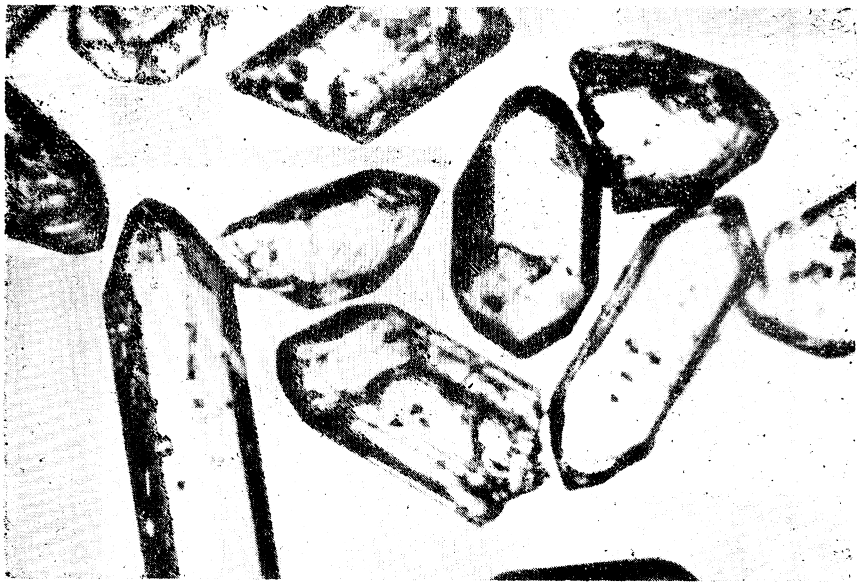
Using the visual descriptions of these samples, one might speculate that the zircons of the Adamstown Granite (owing to their very dark color) would contain a greater concentration of uranium and thorium than the other samples and that the Lost Nation zircons would have little or no inheritance because of their lack of visible inclusions or cores. As discussed in the next section, only the former inference is correct.

Analytical results.—Of the six plutons of the Highlandcroft Plutonic Suite, isotopic data from five show patterns of varying complexity. Only the Attean Quartz Monzonite, located at the northern end of the plutonic belt in western Maine, has simple U–Th–Pb isotopic systematics. Thus, in order to interpret the isotopic data, three to five splits of zircon from each sample were analyzed. The scattered, non-linear distribution of the data on concordia diagrams is in contrast with that of the apparently coeval Oliverian Plutonic Suite (Zartman and Leo, 1985) for which a discordia was calculated through a semi-linear array of data points, yielding an upper intercept (intrusive age) of 444 ± 8 Ma.

In general, zircons from the Highlandcroft Plutonic Suite contain normal concentrations of uranium and thorium (300-800 ppm U and 90-

PLATE 1

A.



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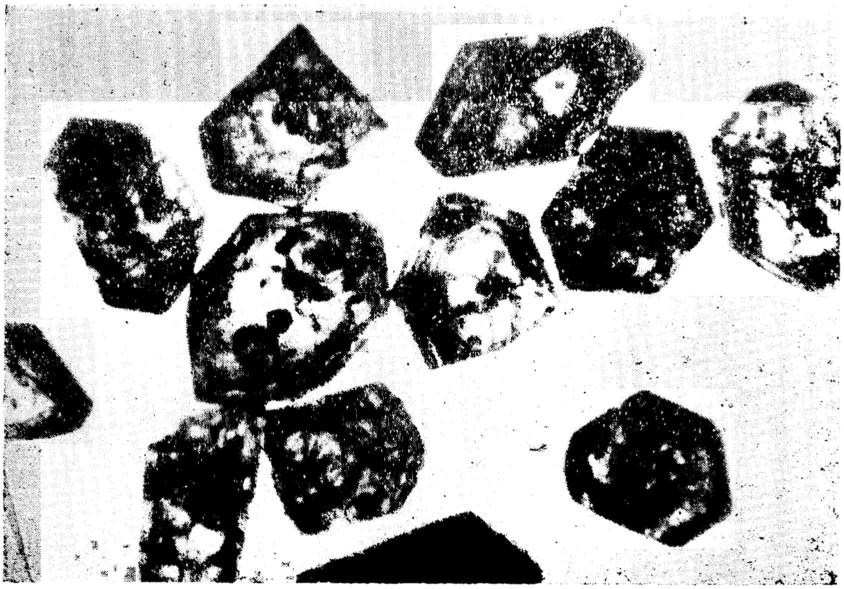
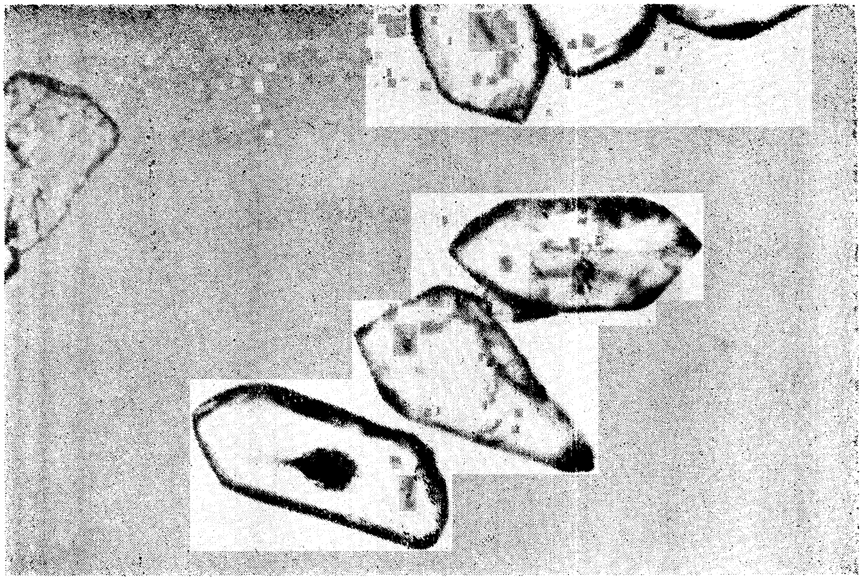


Photomicrographs of dated Highlandcroft Plutonic Suite zircons from (A) Attean Quartz Monzonite (−100 + 150), (B) Adamstown Granite (+150), (C) Lost Nation pluton (−150 + 200), (D) Highlandcroft Granodiorite (−100 + 150), (E) Fairlee Quartz Monzo-

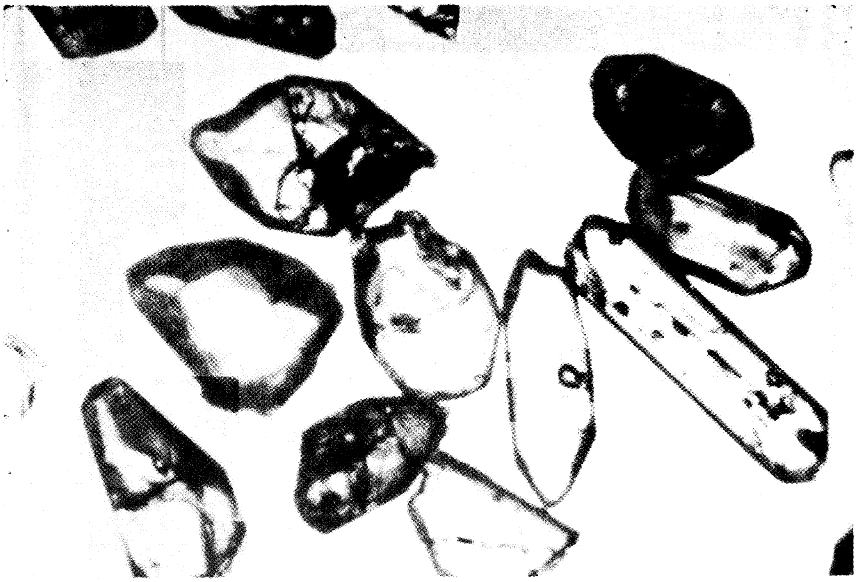


C.

D.

nite (−100 + 150), (F) East Inlet pluton (−150 + 200). Note wide variety in zoning, number, and appearance of inclusions and in length-to-width ratios. Largest grains in (−100 + 150) and (+150) fractions are about 170μ long; largest grains in (−150 + 200) fractures are about 145μ long.

E.



F.

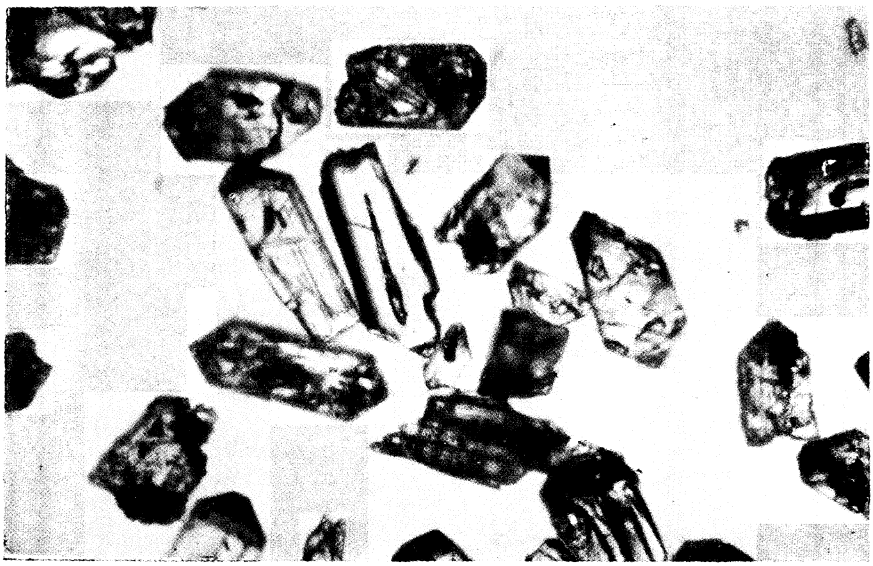


TABLE 1

U–Th–Pb isotopic data for zircons from the Highlandcroft Plutonic Suite

Sample		Concentration (ppm) U	Th	Pb	Atomic percent ^{204}Pb	^{206}Pb	^{207}Pb	^{208}Pb	Ages (Ma) $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{208}Pb/^{232}Th$
Attean Quartz Monzonite												
Me/At 1-79	(+100)NMD*	498	442	41.1	.0142	73.99	4.331	21.66	440	441	442	441
	(-100+150)	594	592	35.2	.0113	72.98	4.224	22.99	428	431	444	416
	(-200+250)	682	732	39.3	.0196	71.43	4.269	24.28	416	421	444	399
Adamstown Granite												
Me/O 1-81	(+150)	1960	685	144	.0515	83.86	5.436	10.65	442	443	448	413
	(+150)NMD*	1801	585	130	.0260	85.21	5.154	9.61	443	445	454	431
	(+150)NMA**	1876	609	134	.0138	85.78	5.154	9.21	442	443	450	430
	(-150+200)	2344	765	169	.0376	84.99	5.302	9.67	440	442	450	410
	(-325)NMD*	2038	631	144	.0157	86.11	5.057	8.81	439	442	455	422
Lost Nation pluton												
NH/Wh 1-79	(-100+150)	125	53	8.4	.0341	82.30	5.480	12.28	483	509	626	474
	(-150+200)	361	155	26.3	.0758	80.31	6.000	13.61	478	506	639	472
	(-200+250)	419	169	25.8	.0731	81.02	5.820	13.08	440	459	556	439
	(-325)NM	493	200	36.8	.0342	82.87	5.197	11.90	443	449	480	438
Highlandcroft Granodiorite												
NH/L 2-79	(-100+150)	384	198	22.5	.1586	75.19	6.530	18.11	409	417	458	413
	(-200+250)	428	225	26.0	.0616	79.00	5.320	15.61	434	437	453	438
	(-250+325)	434	238	33.4	.0687	78.18	5.383	16.37	428	432	454	432
	(-325)	547	452	57.9	.3552	62.49	8.679	28.48	430	433	453	432
Fairlee Quartz Monzonite												
OL-170A	(-100+150)	396	90	23.0	.0702	85.39	5.880	8.66	416	427	485	404
	(-150+200)NMD*	417	82	28.3	.0313	88.35	5.503	6.11	432	442	496	383
	(-200+250)	483	84	27.9	.0635	87.05	5.830	7.05	414	422	465	400
	(-325+400)	611	98	39.7	.0458	88.25	5.821	5.88	413	433	545	379
	(-400)	571	90	36.5	.0197	88.56	5.494	4.93	414	433	535	384
East Inlet Pluton												
NH/SL 1-79	(-100+150)	594	425	34.8	.0281	76.40	4.729	18.35	422	427	459	414
	(-200+250)	886	712	47.7	.0130	75.72	4.387	19.88	391	397	430	387
	(-325)NM	846	652	64.5	.0148	76.19	4.446	19.35	420	422	433	418

* non-magnetic (diamagnetic) — negative side tilt on magnetic separator
** abraded

600 ppm Th), except the zircons from the Adamstown Granite which contain anomalously high amounts of both elements (table 1). Considering all samples, Pb/U isotopic ages range from 391 to 509 Ma with most being in the range from 410 to 440 Ma. However, each sample is unique in its isotopic systematics, and, thus, each will be discussed individually. The following analytical results from the Highlandcroft plutons are presented in a north-to-south order.

Zircons from the Attean Quartz Monzonite (sample Me/At 1-79) have the simplest systematics (fig. 2). Three size fractions of zircon have analytically identical $^{207}Pb/^{206}Pb$ ages (table 1), and the coarsest fraction (+100) NMD, which is composed of the least magnetic zircons, is concordant at 442 Ma. This fraction also contains the least uranium and thorium in the sample (498 and 442 ppm, respectively). A best-fit line calculated through the three data points has intercepts at 443 ± 4 and −23 ± 105 Ma. We interpret these data to indicate a time of intrusion and crystallization of the Attean Quartz Monzonite at 443 ± 4 Ma. Discordance of Pb/U ages was probably caused by recent dilatancy lead loss (Goldich and Mudrey, 1972) as the pluton was exhumed to the surface. Note that there is no inheritance of radiogenic lead in these zircons, that is, no $^{207}Pb/^{206}Pb$ ages older than the age of intrusion. The 443-Ma age on the Attean is confirmed by K–Ar and Rb–Sr muscovite ages. These ages are recalculated using decay constants of Steiger and Jäger (1977) (table 2) and are from the Catheart Mountain Cu–Mo porphyry, which is intrusive into the eastern side of the Attean but is considered to be comagmatic with it (Albee and Boudette, 1972). The mean age of the muscovite data (444 ± 10 my) agrees well with the more tightly constrained zircon age. These data are not in accord with the "informal" U–Th–Pb zircon age of 470 Ma (unpub. data of L. T. Silver). Nevertheless, we conclude that the age of the Attean is 443 ± 4 Ma.

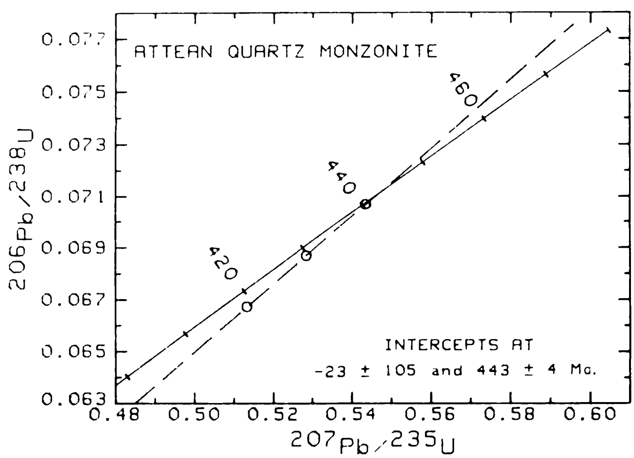


Fig. 2. Concordia plot of zircons from the Attean Quartz Monzonite.

TABLE 2

K–Ar and Rb–Sr isotopic ages of muscovite from a quartz–muscovite–molybdenite vein cutting the Catheart Mountain porphyry of the Attean Quartz Monzonite (sample At-3)

K_2O, %	$^{*40}Ar$, moles/g	$^{*40}Ar/^{40}Ar$	Age (Ma)
10.34	7.421×10^{-9}	0.95	441 ± 8

Decay constants: $\lambda_\beta = 4.962 \times 10^{-10}$ yr^{-1}, $\lambda_e = 0.581 \times 10^{-10}$ yr^{-1}, $^{40}K/K = 0.1167$ atom percent.

Rb, ppm	Sr_n, ppm	$^{*87}Sr$, ppm	$^{*87}Sr/^{87}Sr$	Age (Ma)
495.9	50.0	0.896	0.20	447 ± 10

Decay constants: $\lambda_\beta = 1.42 \times 10^{-11}$ yr^{-1}; age calculated by assuming an initial $^{87}Sr/^{86}Sr$ ratio of 0.705.

The Adamstown Granite (sample Me/O 1-81), located about 80 km southwest of the Attean in west-central Maine, is somewhat different from the other plutons of the Highlandcroft Plutonic Suite, because it contains trace amounts of both scheelite and molybdenite and because the zircons are very dark. These zircons contain between 1800 and 2300 ppm U and 600 to 765 ppm Th, about three to five times higher amounts than for the other plutons in the suite. However, the usually encountered greater discordance associated with high uranium concentration does not occur in these zircons. All five analyzed fractions yield very similar isotopic results which are less than 3 percent discordant (table 1, and fig. 3), although they include very non-magnetic zircon, abraded zircon (with only the cores analyzed), and coarse and fine zircon. $^{207}Pb/^{206}Pb$ ages range

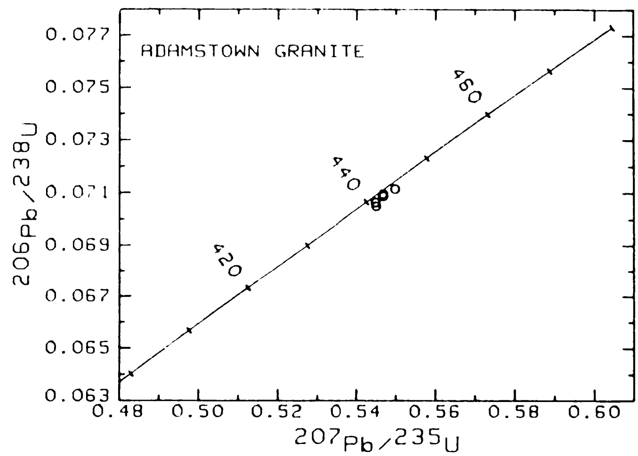


Fig. 3. Concordia plot of zircons from the Adamstown Granite. No meaningful best-fit line calculated, due to non-linearity of data array.

from 448 to 455 Ma, and Pb/U ages range from 439 to 445 Ma. The least magnetic zircons, in the (+150)NMD and (−325)NMD fractions, have $^{207}Pb/^{206}Pb$ ages of 454 and 455 Ma, respectively, whereas the abraded zircons (+150)NMD, have a $^{207}Pb/^{206}Pb$ age of 450 Ma. Because of the tight clustering in the data, no meaningful best-fit line can be calculated, and we conclude, on the basis of evaluation of the five data points, that the age of intrusion of the Adamstown is about 452 ± 4 Ma.

The Lost Nation pluton (sample NH/Wh 1-79) is located about 70 km southwest of the Adamstown Granite in northern New Hampshire. Four size fractions of zircon were analyzed for U–Pb isotopes. Uranium and thorium concentrations range from 125 and 53 ppm, respectively, in the coarsest fraction (−100 + 150), to 493 and 200 ppm in the finest fraction (−325)NMD. These zircons have the oldest $^{207}Pb/^{206}Pb$ ages of any in the Highlandcroft Plutonic Suite, ranging from 480 to 639 Ma (table 1). The data do not form a linear array (fig. 4), probably because of both inheritance and lead loss. An estimate of the age of intrusion can be made based on two assumptions: (1) no lead loss has occurred in the (−100 + 150) fraction because of the extremely low uranium and thorium contents, and (2) the age of inheritance is about 1525 ± 25 Ma.

The validity of the first assumption may be supported by the conclusion of Ludwig and Cooper (1984) that zircons with uranium concentrations below some threshhold value are essentially concordant or nearly concordant (that is, have not lost lead because, at least in part, of a lack of metamictization). In the case of the Lost Nation zircons, the uranium

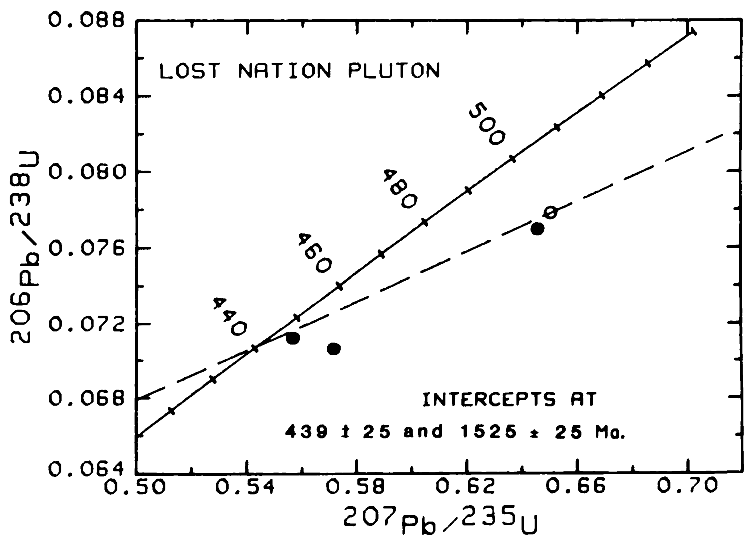


Fig. 4. Concordia plot of zircons from the Lost Nation pluton. Best-fit line calculated through lowest uranium-content fraction (−100 + 150), shown as circle, and 1525 ± 25 Ma. Dots not used in regression calculation. See text for additional explanation.

concentration of 125 ppm is assumed to be so low as not to have caused sufficient radioactive damage to the crystals. Because of its inherited xenocrystic component, the location of that point on a concordia diagram is on a line between the age of inheritance and the age of intrusion. By knowing both the inheritance age and the Pb/U ages of the sample, the lower intercept (intrusion) age can be calculated. Data from Naylor and others (1973) on the Chain Lakes massif (recalculated at 1529 ± 39 Ma) and from Aleinikoff and Moench (1985), who show the age of inheritance of a nearby metavolcanic unit as about 1500 Ma, plus numerous unpublished results from our laboratory, suggested that the inheritance age is about 1525 ± 25 Ma. A discordia calculated through the (−100 + 150) fraction has a lower intercept of 439 ± 25 Ma. This age is in agreement with that of the Attean Quartz Monzonite (443 ± 3 Ma) but may not be correct if either of the two assumptions is invalid. If lead loss has occurred in the (−100 + 150) fraction of zircons, the lower intercept would be too low. If the inheritance age really is somewhat younger, or if lead loss had occurred in the inherited component prior to incorporation in the pluton, then the lower intercept is too high. We suggest that the age may be about 440 Ma but caution that is only a best guess now, and that better age data are needed.

The Highlandcroft Granodiorite (sample NH/L 2-79), at the type locality of the Highlandcroft Plutonic Suite in the Littleton, N.H. quadrangle (15′) is located about 15 km southwest of the Lost Nation pluton. Four size fractions of zircon were analyzed and ranged in uranium concentrations from 384 ppm in the (−100 + 150) fraction to 547 ppm in the (−325) fraction. The three finest fractions (table 1) have identical $^{207}Pb/^{206}Pb$ ages of about 453 Ma, and the (−100 + 150) fraction has only a slightly older $^{207}Pb/^{206}Pb$ age of 458 Ma. Based on analyses of other samples from the Highlandcroft Suite, the older age in the coarse fraction is

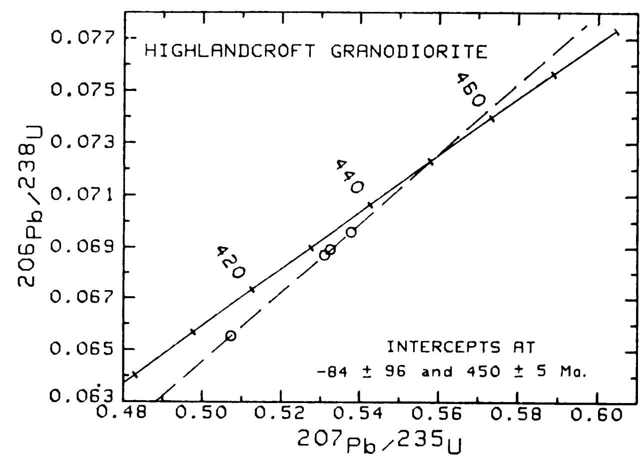


Fig. 5. Concordia plot of zircons from the Highlandcroft Granodiorite.

likely due to a slight amount of inheritance of radiogenic lead. However, the difference in ages is within analytical uncertainty, and a best-fit line calculated through all four points (fig. 5) has an upper intercept (intrusion) age of 450 ± 5 Ma, with discordance being due to recent dilatancy lead loss (Goldich and Mudrey, 1972). We conclude that the Highlandcroft Granodiorite and Adamstown Granite are essentially coeval at 450 to 452 Ma.

The Fairlee Quartz Monzonite (sample OL-170A) is located about 50 km southwest of the Highlandcroft Granodiorite in east-central Vermont. Five fractions of zircon have been analyzed, only one of which was also magnetically split. The four size fractions not magnetically split have nearly identical $^{206}Pb/^{238}U$ ages (413-416 Ma) but a wider range in $^{207}Pb/^{235}U$ ages (422-433 Ma), with the resulting $^{207}Pb/^{206}Pb$ ages ranging from 465 to 545 Ma. The (−150 + 200)NMD fraction, containing only very non-magnetic zircons, has an intermediate $^{207}Pb/^{206}Pb$ age (496 Ma), as could be predicted by the progressive increase in $^{207}Pb/^{206}Pb$ age with decreasing grain size. The Pb/U ages from the (−150 + 200)NMD fraction are slightly older than in the other fractions (432 and 442 Ma) but still are quite discordant. The scatter pattern of data shown in figure 6 again indicates the occurrence of both an inherited lead component and later lead loss. Because this rock is at fairly low grade and contains zircons with fairly low uranium concentrations, and because no other plutons of the Highlandcroft Suite show any evidence for a geologic disturbance to the isotopic systematics prior to modern lead loss, we suggest that the lead loss in the Fairlee zircons also occurred recently. If so, the $^{207}Pb/^{206}Pb$ age would not change when lead loss happened, and, thus, the only constraints provided by the zircon data are that the rock must be no older than 465 Ma. When compared with other Highlandcroft Suite results and geologic

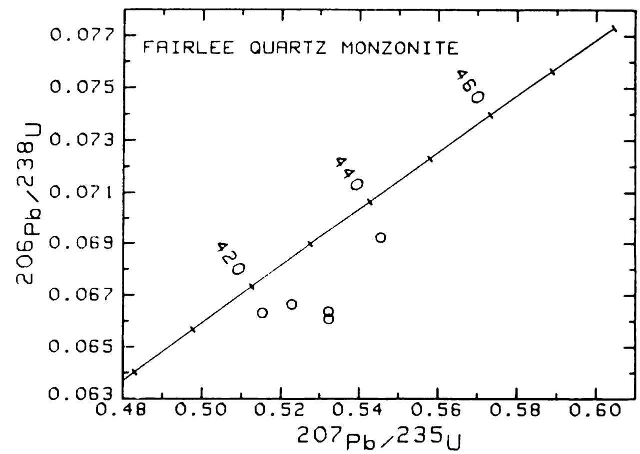


Fig. 6. Concordia plot of zircons from the Fairlee Quartz Monzonite. No meaningful best-fit line calculated due to non-linearity in data array.

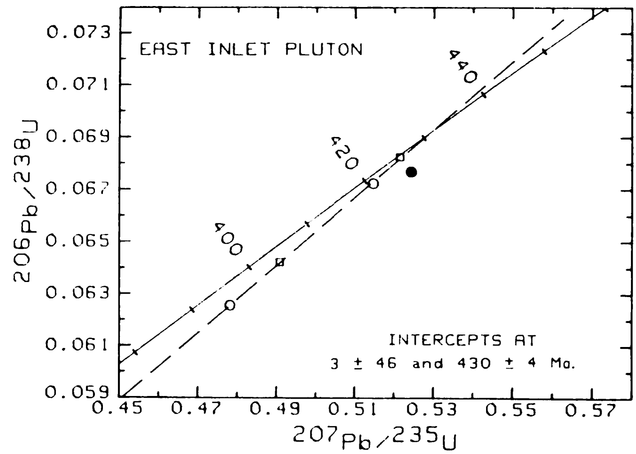


Fig. 7. Concordia plot of zircons from the East Inlet pluton. Best-fit line calculated through two points (circles) from this study plus two points (open squares) from Eisenberg (ms). Solid symbol not used in regression calculation.

constraints, this maximum age is somewhat high, and, thus, it seems likely that all analyzed fractions of zircon in the Fairlee Quartz Monzonite contain some inheritance. This means we have not been able to directly date this rock. Naylor's (1969) Rb–Sr whole-rock determination of 450 ± 40 Ma for the Fairlee has a similar degree of uncertainty.

Recent mapping by R. H. Moench (verbal commun.) shows the Fairlee Quartz Monzonite to be fault-bounded, but intrusive at its northern end into the Silurian Perry Mountain Formation. Geologically, therefore its age appears to be Early to Middle Silurian or younger. One possibility is that it is an age equivalent of the East Inlet pluton.

The East Inlet pluton (sample NH/SI 1-79) occurs about 20 km northwest of the trend of the other Highlandcroft Suite plutons in northern New Hampshire (fig. 1). We analyzed three size fractions (table 1), in addition to the four reported by Eisenberg (ms). The coarse fraction from the East Inlet has an older $^{207}Pb/^{206}Pb$ age (459 Ma) than the finer fractions (433 and 430 Ma). We interpret these data to indicate an intrusive age of about 430 Ma, with the coarse zircons containing older xenocrystic inheritance. This crystallization age is consistent with two (of four) fractions from Eisenberg (ms), including a nearly concordant "total" fraction. When the four points are regressed (fig. 7), the discordia has intercepts at 430 ± 4 and 3 ± 46 Ma. Thus this body is about 10 to 25 Ma younger than the other plutons of the Highlandcroft Suite but lies off the main strike belt, and perhaps it should not be classified with them.

In summary, the Highlandcroft Plutonic Suite is composed of bodies of quartz monzonite to granodiorite that range in age from about 453 to 430 Ma. The two northernmost plutons, the Attean Quartz Monzonite and Adamstown Granite (443 and 452 Ma, respectively), contain zircons that have little or no inherited component. To the south, the Lost Nation pluton (about 440 Ma(?)) contains zircons with a relatively large proportion of xenocrystic inherited lead, even though this material is not visible in microscopic examination of the zircons. Zircons from the Highlandcroft Granodiorite (450 Ma) contain a small amount of inheritance, and zircons from the undatable Fairlee Quartz Monzonite contain a larger inherited component. The East Inlet pluton (430 Ma) is distinctly younger than other dated plutons of the Highlandcroft Suite.

DISCUSSION

The seven Oliverian dome rocks recently dated by Zartman and Leo (1985) have U–Th–Pb ages coeval (with the exception of the East Inlet pluton) with those we have determined for the Highlandcroft Plutonic Suite (442-453 Ma), but differences in the inherited lead pattern are striking. None of the Oliverian dome rocks shows any evidence of inherited lead, but four of the six plutons we have examined show, by inference from the isotopic data, varying amounts of contamination by older, partially digested zircon.

Our interpretation of this difference is that the magmas of the Highlandcroft and Oliverian Plutonic Suites originated in different paleogeologic environments. Using geologic-petrologic evidence, Lyons, Boudette, and Aleinikoff (1982) and Robinson and Hall (1980) have shown that the present course of the Connecticut Valley in New England is a fundamental tectonic boundary coinciding approximately with a fossil easterly-dipping subduction zone active at least into Middle of Late Ordovician time. In central Vermont, the Late Proterozoic basement, where exposed in the Green Mountains and Ludlow Dome west of this tectonic boundary, is of Grenvillion (1 Ga) age. We can now conclude that basement at least this old (but probably as old as 1.5 Ga) or material eroded from a 1.5-Ga old provenance extends northeasterly across northernmost New Hampshire, northwest of the projected strike of the Ammonoosuc fault (fig. 1). The same basement age (1.5 Ga) has been deduced by Aleinikoff and Moench (1985) from U–Pb isotopic data for the region in northeastern New Hampshire midway between the Attean and Lost Nation plutons. By contrast, such basement seemingly does not occur along the belt of Oliverian domes of the Bronson Hill anticlinorium, as inferred by the lack of an inherited radiogenic lead component in the zircons, as well as by relatively low (.705) $^{87}Sr/^{86}Sr$ initial ratios (Naylor, 1969). Evidence for old basement is also not present in the vicinity of the Adamstown pluton, nor in the region immediately east of the Chain Lakes massif (fig. 1). However, east of the Bronson Hill anticlinorium in central western New Hampshire, there is convincing isotopic evidence of additional 1.5 Ga basement (Barreiro and Aleinikoff, 1985). Work we now have in progress shows that granites of the New Hampshire Plutonic Suite (Devonian and younger) in central New Hampshire also have old xenocrystic zircon, implying that a Proterozoic crust, or sediments derived therefrom, likewise underlies this region.

The tectonic pattern, which emerges from this distribution of ages, is one in which there is a suture between Grenvillian (1 Ga) and Chain

Lakes (1.5 Ga) blocks, approximately along the trace of the Monroe fault (fig. 1). The Lower Paleozoic Vermont sequence covering the Grenville is not directly correlative with, nor can it be traced directly into, the Lower Paleozoic New Hampshire sequence east of the Monroe fault. This suggests that the fault is a major tectonic boundary juxtaposing two distinctly different lithotectonic blocks. To the east, below the Bronson Hill anticlinorium, is apparently oceanic (?) basement or very thin Precambrian crust, but to the east of this in New Hampshire, more extensive Chain Lakes basement.

The anticlinorium, with its association of Middle(?) Ordovician Ammonoosuc Volcanics and euxinic Partridge and Quimby schists, and its Oliverian domes, has long been considered an Early Paleozoic island arc (Naylor, 1969; Thompson and others, 1968). This suggestion is supported by petrochemical studies of the Ammonoosuc Volcanics (Aleinikoff, 1977; Leo and Gromet, 1981; Schumacher, ms; Shumway, ms; Leo, 1985) which show they have a provenance comparable to that of modern oceanic island arcs, continental margin arcs, and abyssal tholeiites. Schumacher (ms) suggests that the best modern analogue is the Tonga arc. The presence of alpine serpentinites in the Ordovician belt fringing the western side of the Bronson Hill anticlinorium and the fact that this belt traces northerly toward the Cambrian Boil Mtn. ophiolite of western Maine (Boudette, 1981) has led to a suggestion that it may also be another major suture zone of Iapetus (Lyons, Boudette, and Aleinikoff, 1982). Alternatively, the Bronson Hill terrane may be a now-closed rifted back-arc basin above an easterly-dipping subduction zone whose present surface expression is the Monroe fault.

If, as we suppose, the magmas of the Oliverian Plutonic suite were generated in a back-arc (easterly) region, the plutons ascended into a stack of volcanics and through volcaniclastic sediments which were almost coeval with them. Highlandcroft magmas generated in the forearc and trench environment to the west rose through continental crust of Grenvillian or older age and were contaminated by it. Telescoping of the two suites has been effected by both Taconian and Acadian tectonism.

Additional evidence for this conclusion is afforded by the U/Th ratios of the zircons which show a correlation between those ratios and the degree of inheritance. The Lost Nation and Fairlee plutons, with the largest amounts of xenocrystic zircon, have U/Th ratios from 2.5 to 6, but in the Attean, Highlandcroft, and East Inlet plutons where there is little or no contamination, the ratios range from 0 to 1.9. An exception to the generalization that a high U/Th ratio is indicative of xenocrystic zircon is the Adamstown pluton in which the ratio is 2.9 to 3.2, but in which there is no other evidence of inheritance of older zircons. The data are insufficient to deduce an unambiguous explanation; one possibility is that magmas derived from oceanic source rocks contain no old xenocrysts and have relatively low U/Th, but magmas originating in, or strongly contaminated by, continental crust will have high U/Th ratios.

Both the Oliverian and Highlandcroft intrusive suites are metaluminous, which means that their zircon saturation values are low (Watson, 1979). The spectrum of chemical compositions in the two series is also quite similar (Pogorzelski, ms) and insufficient to cause vastly different zircon solubilities as would be true, for example, if one of the series were alkaline or peralkaline. Because magma composition does not explain the different degrees of xenocrystic zircon inheritance in the two series, we rationalize that different magma source regions — oceanic for the Oliverian and continental for the Highlandcroft — provide the best explanation of the different U–Th–Pb systematics in the zircons of the two series.

Billings (1937, p. 480) originally considered the regionally associated Ammonoosuc Volcanics to be "probably Upper Ordovician" but later (1956, p. 19) thought "the formation might be Middle Ordovician." The Highlandcroft Plutonic Suite was assigned by him to the Early Late Ordovician and the Oliverian Series to the Middle or Late Devonian(?). Age estimates of the boundaries of the different geological periods or epochs (Van Eysinga, 1975; Harland and others, 1982; Palmer, 1983) appear to be in agreement that the Ordovician time boundaries span the interval between about 500 and 430 Ma and that the Middle to Late Ordovician boundary is at 458 ± 12 Ma. On this basis, the 440 to 450 Ma isotopic ages of much of the Highlandcroft and Oliverian Plutonic Suites would be classified as Late rather than Middle Ordovician, but the uncertainty in the exact age of the boundary precludes a definite epoch assignment. Aleinikoff and Moench (1985) have reported a 464 ± 4 my U–Pb isotopic zircon age on subvolcanic intrusives cutting the Ammonoosuc Volcanics in northern New Hampshire which establishes a minimum age for them. That age is consistent, as they point out, with the occurrence of Middle Ordovician graptolites found in black shales intercalated with Ammonoosuc greenstones in western Maine.

Whatever the resolution of these discrepant age assignments for the Highlandcroft Suite, magmatism in northwestern New England has clearly been a continuing process from the Ordovician through at least the Devonian. There is not only the 430-Ma East Inlet Pluton (Early Silurian on all time scales quoted in the preceding paragraph) but also a series of 415 to 420 Ma hypabyssal rocks (Lyons, Zartman, and Aleinikoff, 1983; Eisenberg, ms) extending over a wide area of northwestern Maine and northern New Hampshire. Furthermore, Devonian magmatism, both syn- and post-tectonic (approx 410-380 Ma) is well-documented in New England (Lyons and Livingston, 1977). Thus, as more igneous rocks from New England are dated, it now appears that magmatism occurred not only during discrete thermal pulses but also was semi-continuous throughout most of the early and middle Paleozoic.

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Appendix 1

Sample locations

Sample number	Latitude N	Longitude W	Description
Me/At 1-79	45°33′54″	70°18′30″	Attean Quartz Monzonite Light green, porphyritic, epidotized and chloritized granite.
At-3	45°32′10″	70°12′30″	Attean Quartz Monzonite Light pink quartz–feldspar porphyry of Cathcart Mountain.
Me/O 1-81	44°59′12″	70°51′12″	Adamstown Granite Coarse-grained, gray, and pink strongly sheared and metamorphosed granite.
NH/Wh 1-79	44°26′54″	71°34′40″	Lost Nation pluton Greenish-gray, medium-grained metamorphosed quartz diorite
NH/L 2-79	44°19′20″	71°48′58″	Highlandcroft Granodiorite Greenish-gray sheared, medium-grained metamorphosed granodiorite.
OL-170A	43°54′57″	72°08′07″	Fairlee Quartz Monzonite Weakly foliated, pink, medium to coarse-grained metamorphosed granite.
NH/SL 1-79	45°11′33″	71°07′37″	East Inlet pluton Green-gray, medium-grained quartz monzonite.

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